Space environment

1. Introduction
2. Space environment bases
3. Sources of energetic particles
4. Outside the near-Earth environment
5. Conclusion

Introduction

Introduction

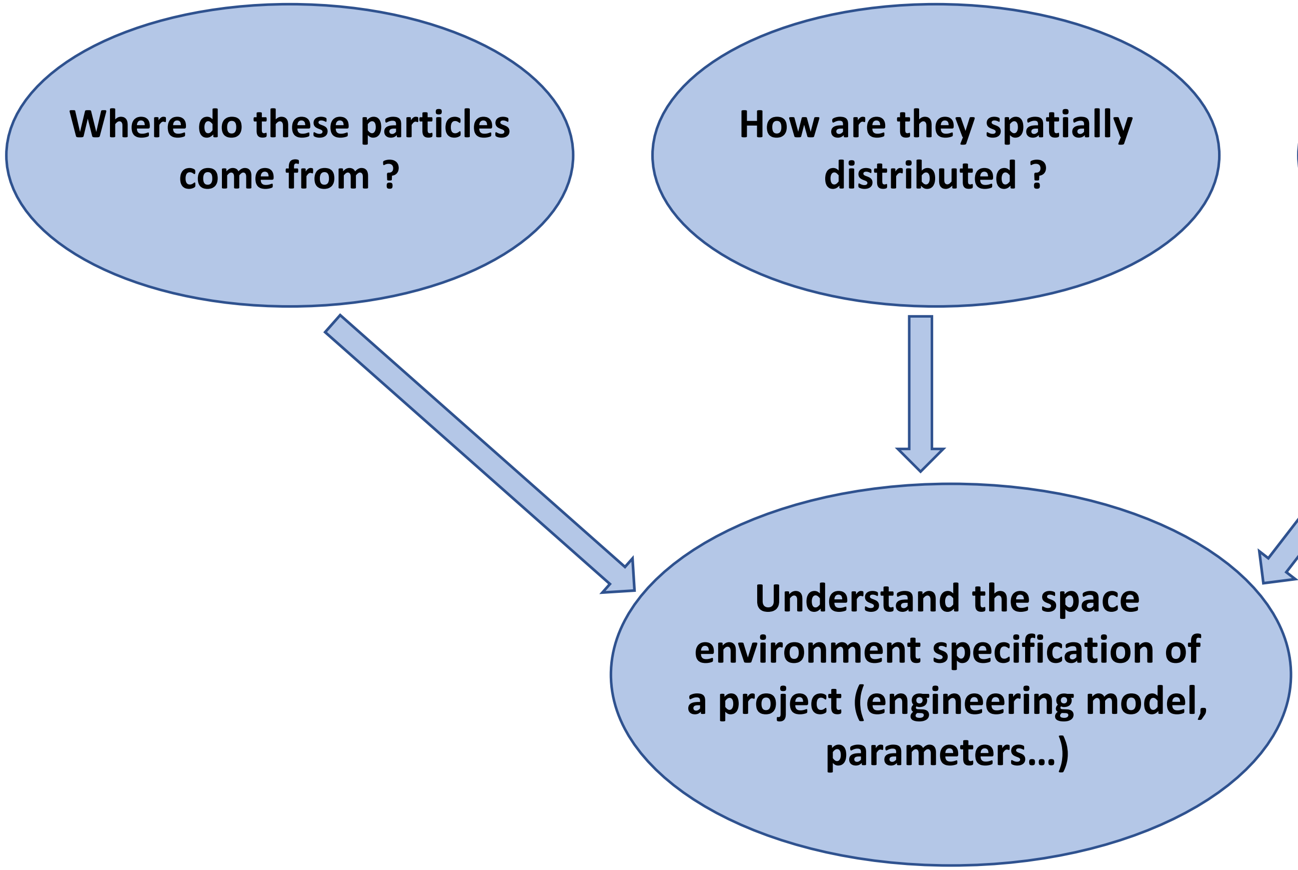
- High-energy particles on satellites:
  - Single Events Effects → Transient or permanent effects caused by 1 particle
  - Ionizing dose
  - Non-ionizing dose
  - Effects depends on particles type, energies and fluxes : **Space environment**

- Amount of particles depends on the mission:
  - Orbit (different particle spectra according to the position above the Earth)
  - Date of launch (solar activity dependency)
  - Duration

- Three sources of high-energy particles :
  - Solar particles
  - Galactic Cosmic Rays
  - Trapped particles

Introduction

- Objectives : global picture of our space environment



Introduction

- Objectives : global picture of our space environment

PROBA 3 Environmental Specification
issue 2 revision 0
P3-EST-RS-6003

Table-2: Standard field models to be used with radiation-belt models

Radiation-belt Model	Geomagnetic Field Model
AE-8-MIN	Jensen-Cain 1960
AE-8-MAX	Jensen-Cain 1960
AP-8-MIN	Jensen-Cain 1960
AP-8-MAX	GSFC 12/66 extrapolated to 1970

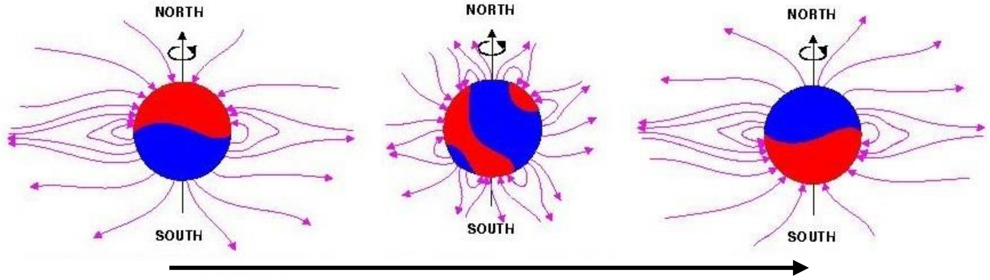
Tests & radiations
a HEICO company

Space environment bases

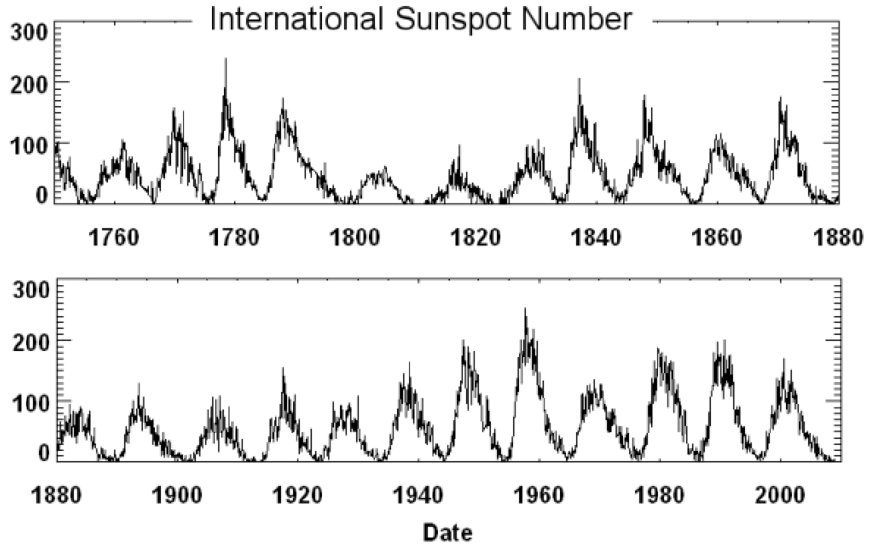
- **Solar cycle**
- **Magnetosphere**
- **Magnetospheric shielding**
- **Particle spectra**

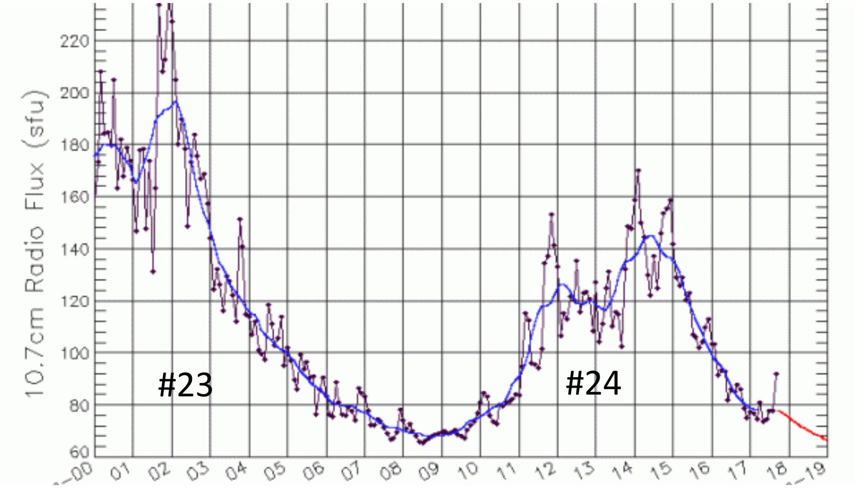
Solar cycle

- Solar magnetic field
  - 11 years cycle (approximately)
  - Dipole during solar minimum
  - Complex during maximum



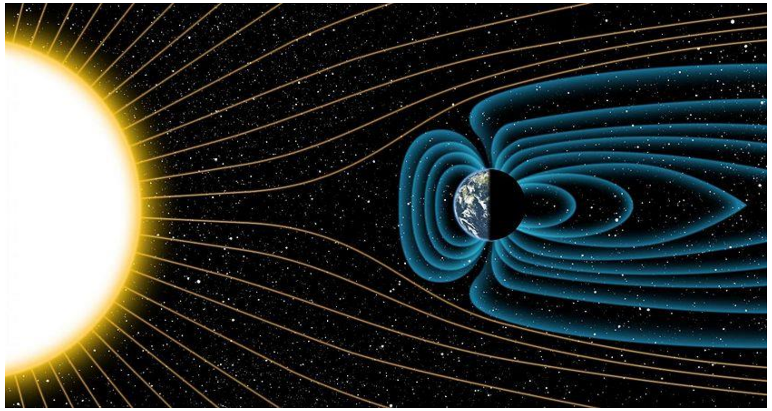
- Solar activity has an impact on:
  - Galactic cosmic rays
  - Solar flares
  - Trapped particles





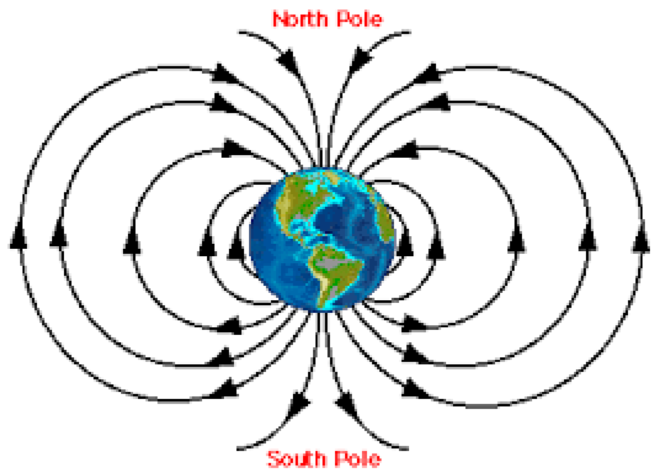
Today: Solar cycle #25
- Min started in 2020
- Max would be reached in 2024

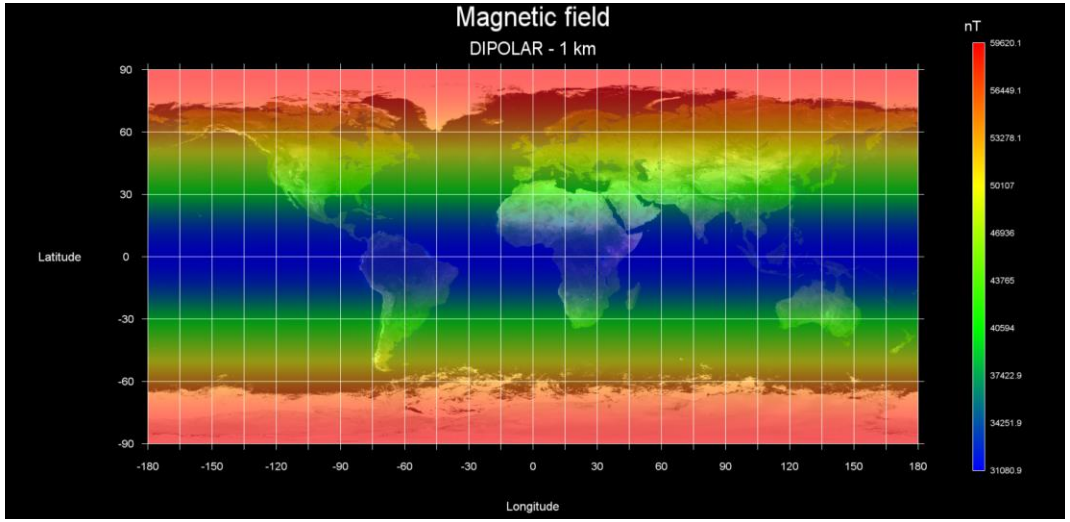
Magnetosphere



- Magnetosphere:
  - Cavity where the magnetic field dominates
  - Undergoes the pressure of the solar wind
  - **Natural protection** for the satellites (from cosmic rays and solar flares).
  - **Trapping** of lower energetic particle

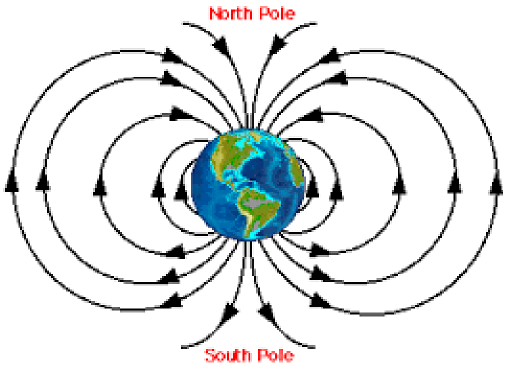
- Earth magnetic field (B_{earth})
  - Dipole

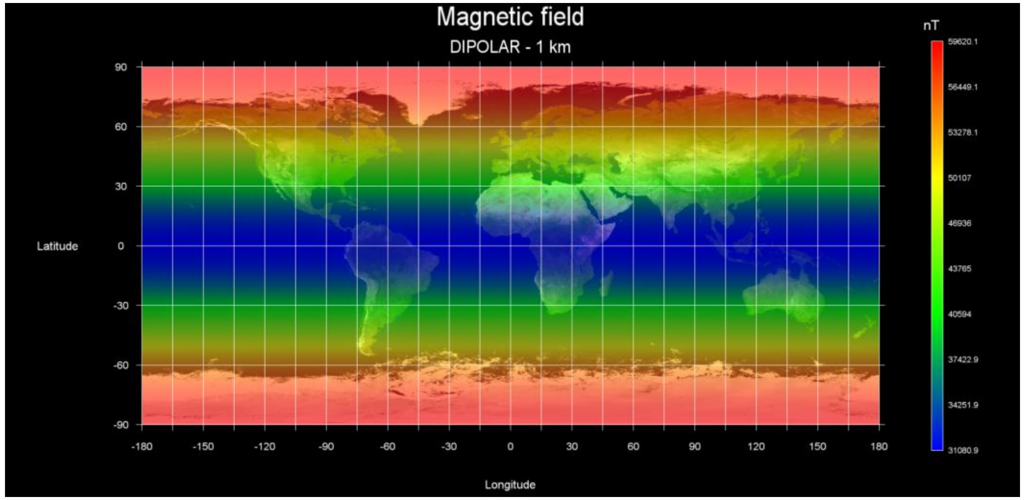




Magnetosphere

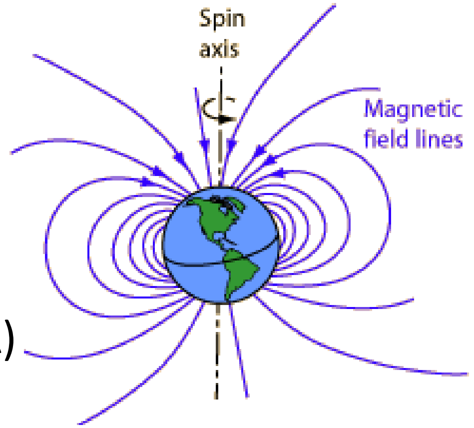
- Earth magnetic field (B_{earth})
  - Dipole
  - No tilt
  - Dipole center and rotation center at the same location

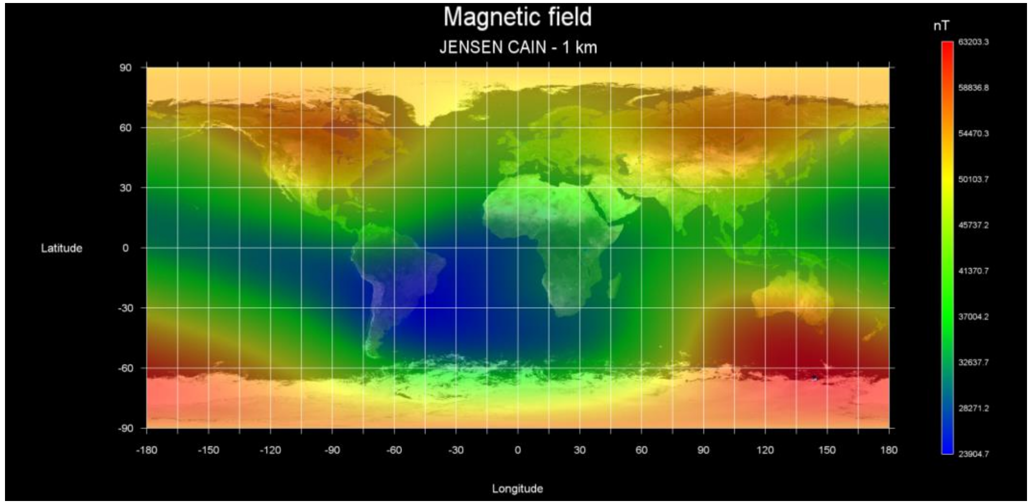




  - Dipole
  - Tilted wrt spin axis (11°)
  - Off-centered (500 km)

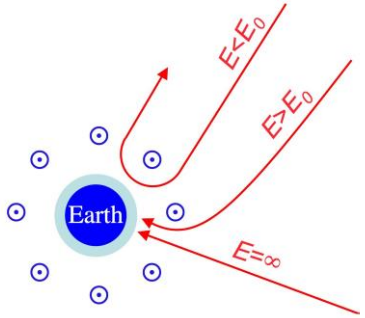
→ South Atlantic Anomaly (SAA)



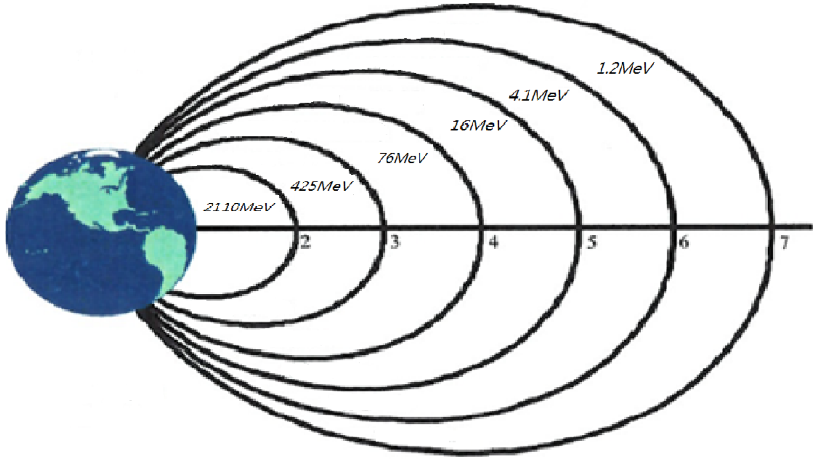


Magnetospheric shielding

- Charged particles are deflected by the magnetic field



- Magnetospheric shielding:
  - Particles have to be very energetic to reach low altitude orbits
  - Function of the energy level
  - Electrons can not penetrate the shield
  - No protection near the magnetic poles
  - **Efficient against solar particles and cosmic rays**



Magnetospheric shielding as a function of L.

L : McIlwain parameter

Particle spectra

- What is a particle spectra ?

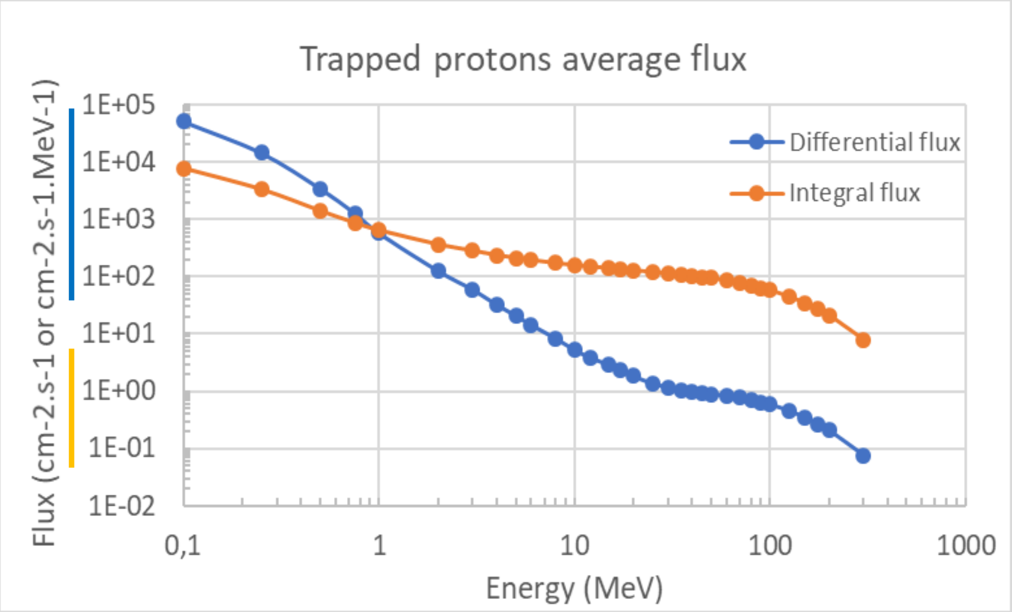
  - Gives the amount of a given particle above or at a given energy

  - The quantity of particle is expressed as a flux or a fluence:
    - **Flux**: Number of particles crossing a surface per time unit **[$cm^{-2}.s^{-1}$]**
    - **Fluence**: Total number of particles crossing a surface during a given time **[cm^{-2}]**

  - Two different kinds of spectra:
    - **Differential**
    - **Integral**

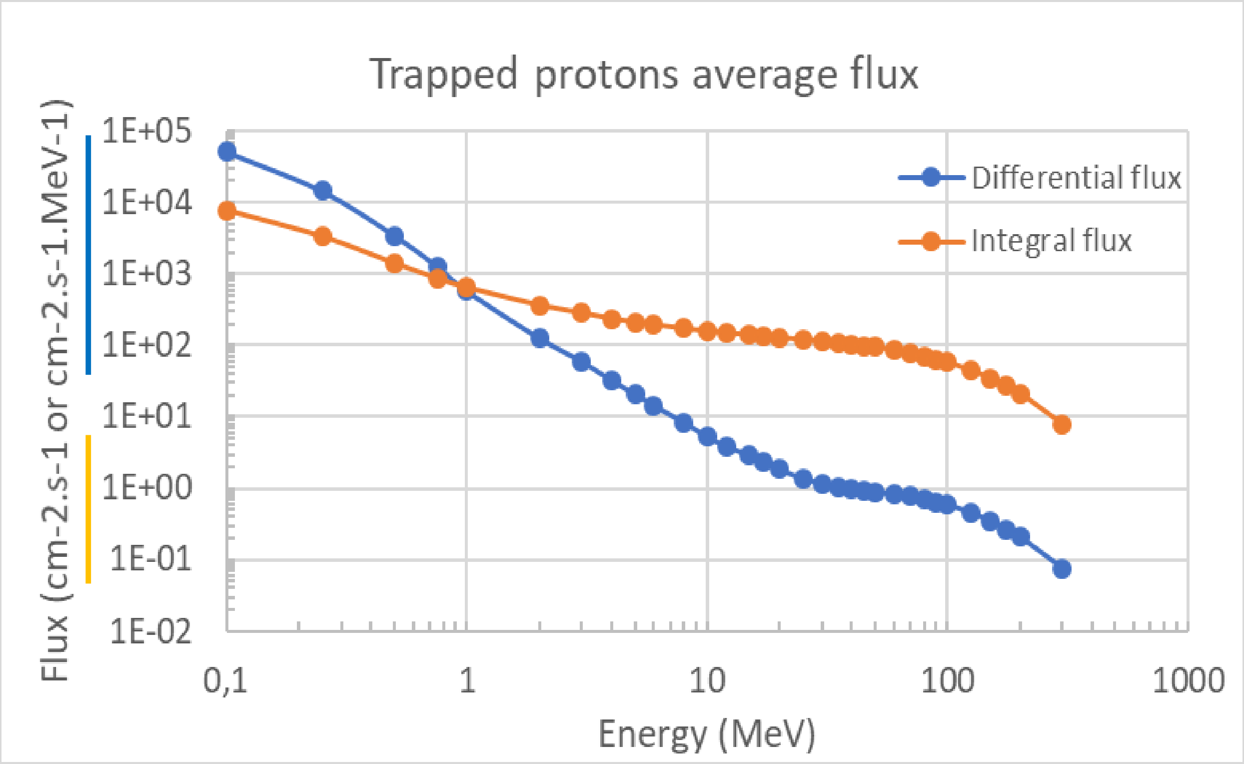
  - Output of **engineering space environment model**

Proton flux for a typical LEO mission (AP8 min)



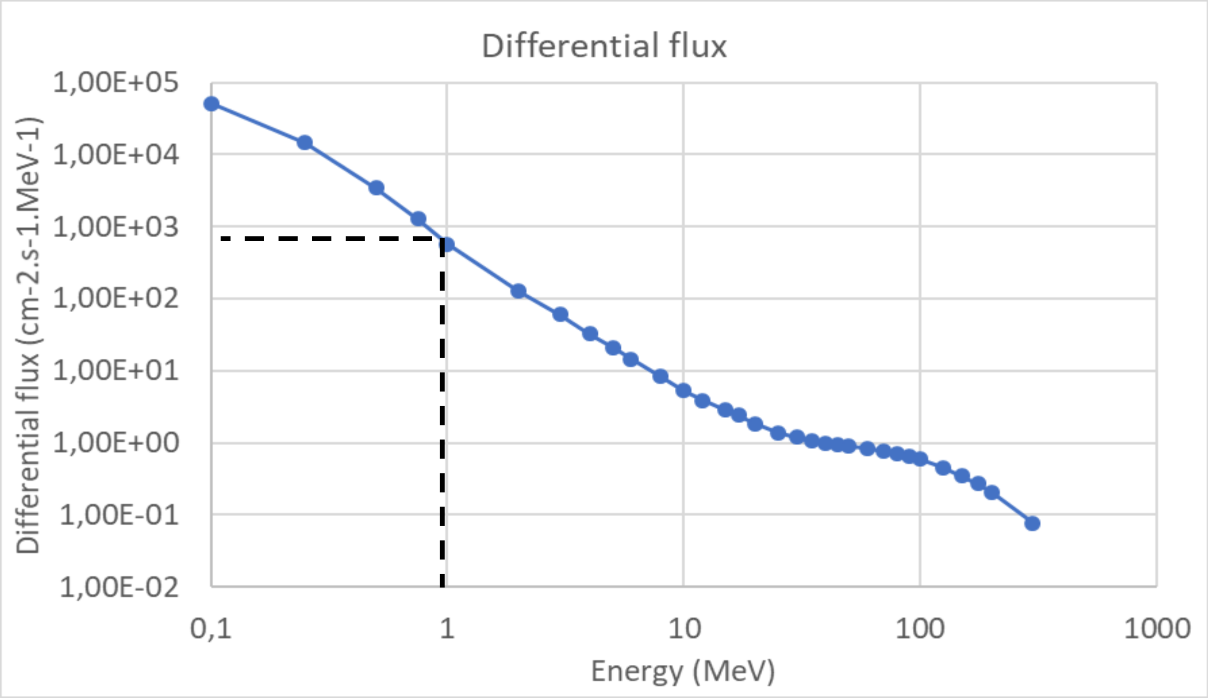
Particle spectra

- Remark : Differential flux can be higher than the integral flux
  - Normal
  - Not comparable
  - Not the same unit



Particle spectra

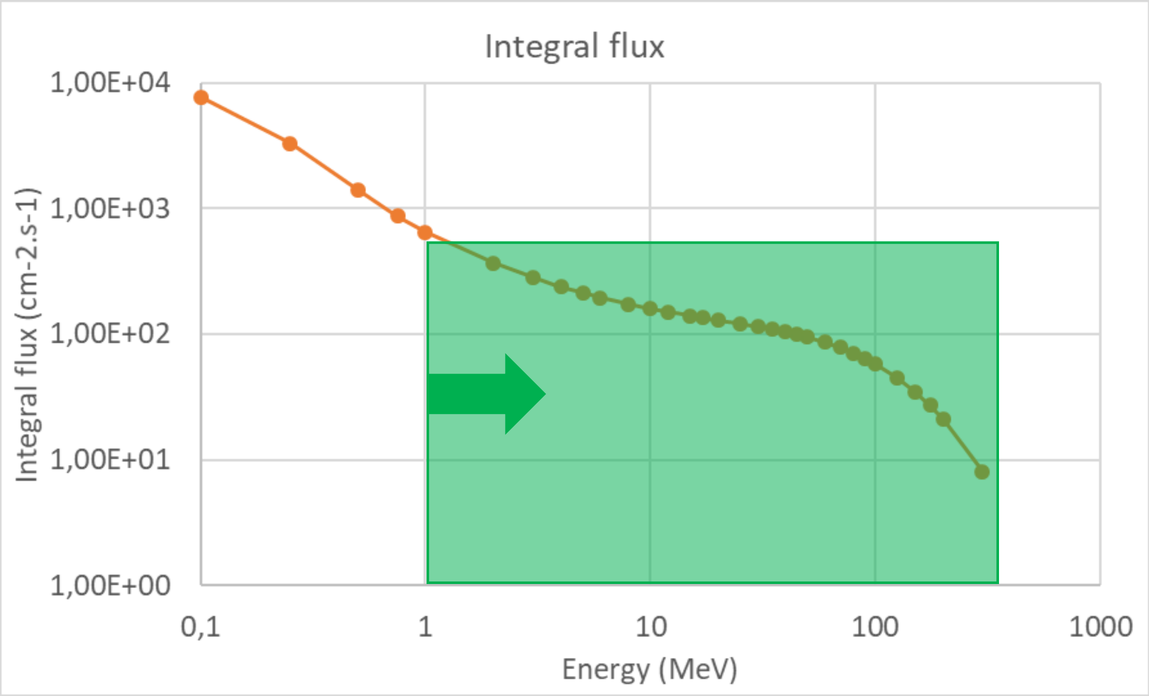
- Differential
  - Flux (or fluence) of particles **around a given energy**
  - Units: [$cm^{-2}.s^{-1}.MeV^{-1}$] (or [$cm^{-2}.MeV^{-1}$])



Example: Approximately 900 particles $cm^{-2}.s^{-1}.MeV^{-1}$ **around** 1 MeV

Particle spectra

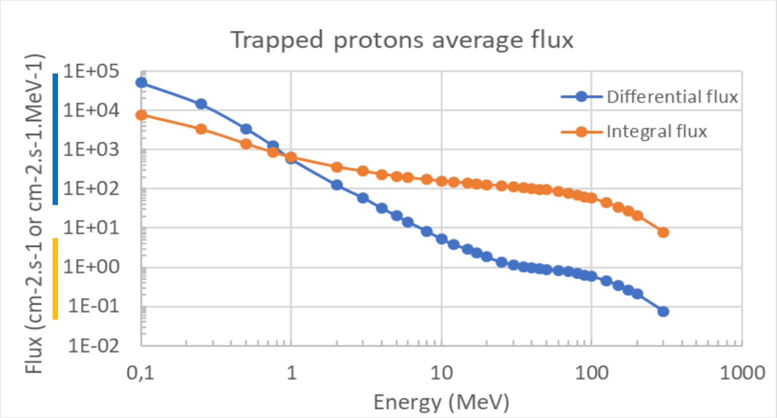
- Integrated
  - Flux (or fluence) of particles **above a given energy**
  - Units: [$cm^{-2}.s^{-1}$] (or [cm^{-2}])



Example: Approximately 800 particles $cm^{-2}.s^{-1}$ **above** 1 MeV

Particle spectra

- Flux
  - Number of particles crossing a surface per time unit
  - Units: [$cm^{-2}.s^{-1}$]
- Fluence
  - Total number of particles crossing a surface during a given time
  - Units: [cm^{-2}]
- Differential
  - Flux (or fluence) of particles around a given energy
  - Units: [$cm^{-2}.s^{-1}.MeV^{-1}$] (or [$cm^{-2}.MeV^{-1}$])
- Integrated
  - Flux (or fluence) of particles above a given energy
  - Units: [$cm^{-2}.s^{-1}$] (or [cm^{-2}])



Summary

- Three sources of high energy particles :
  - Solar particles
  - Galactic cosmic rays
  - Trapped particles

- The solar cycle has an influence on these particle sources
- The Earth magnetic field:
  - Protects us from the particles coming from outside (Magnetospheric shielding)
  - Particle trapping

- The space environment is specified for a mission with particle spectra
  - How many particles, and at which energy ?
  - Averaged number of particle
    - Over time
    - Usually over all space directions (4π sr)
  - Differential or Integrated over energy
    - Unit $cm^{-2}.s^{-1}.MeV^{-1}$ or $cm^{-2}.s^{-1}$

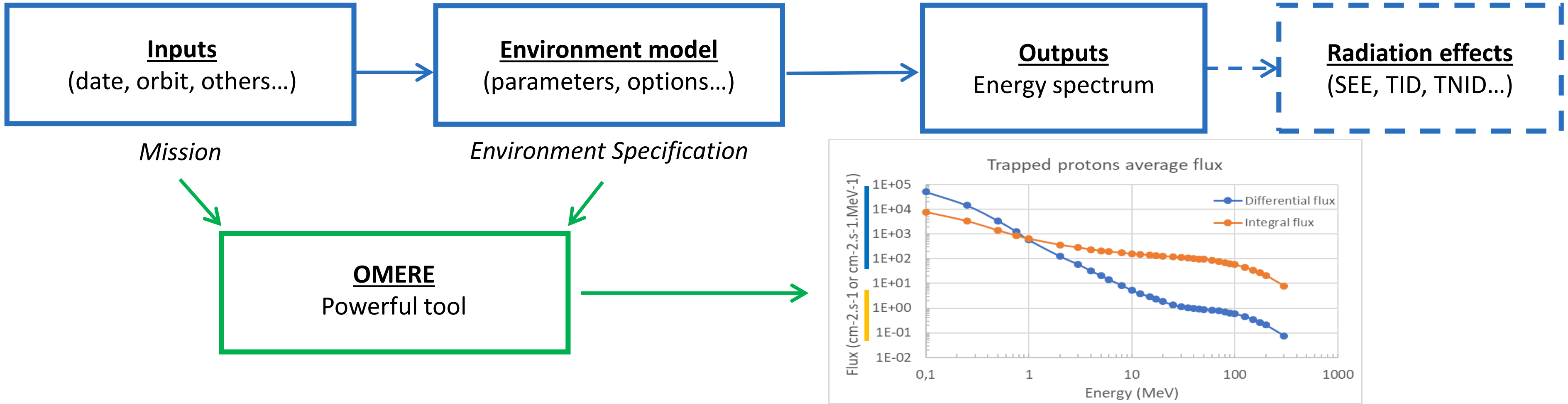
Source of energetic particles

- Solar particles
- Galactic Cosmic Rays (GCR)
- Trapped particles

Sources of energetic particles

- Two main objectives:
  - Know the physical origins of each particle source
  - Understand the meaning of the standard space environment models and their parameters

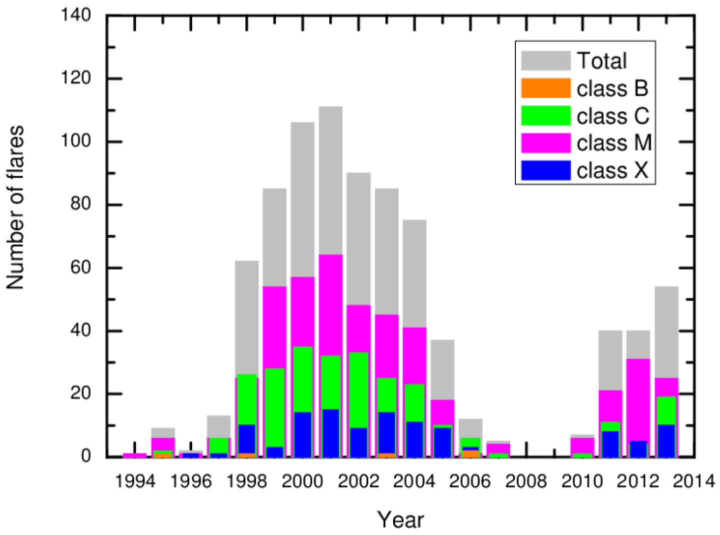
- What is a space environment model ?
  - Estimation of the particle fluxes of a given source during the mission
  - Based on satellite measurements
  - Depends on parameters



Solar particles

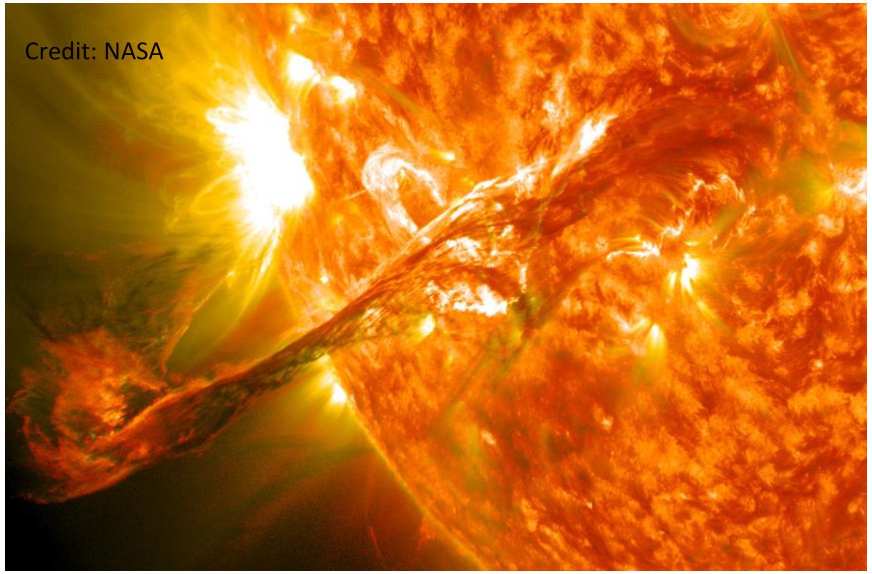
Solar particles

- **Solar flares** : particles ejected from the Sun with relativistic speeds
- **Duration** : hours to days
- **Energy** : up to a few 100 MeV
- **Composition** : protons (> 50%) and ions (strongly depends on the flare)
- **Number of flares correlated with the solar cycle**

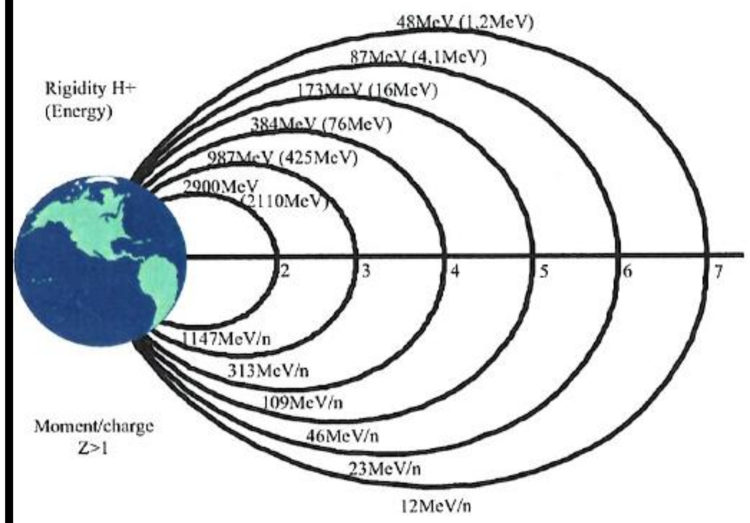


Increasing intensity (W/m²): B → C → M → X

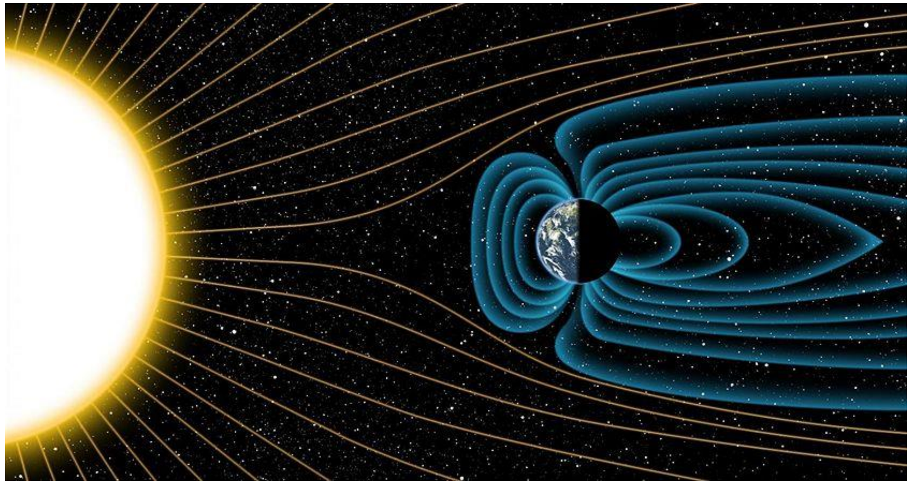
x10 x10 x10



Solar particles



Magnetospheric shielding – rigidity (or energy in parentheses) as a function of L.



- Significant for :
  - High altitude orbits (high perigee, apogee)
  - High latitude orbits (high inclination)
  - Interplanetary trajectories

Solar particle models

- Two families of solar particle models:
  - **Average statistical models**
  - **Solar Flare models**

- Each family is used to compute a defined type of radiation effects:
  - Average models → Cumulated effects (Ionizing and Non-ionizing Doses)
  - Flare models → Single Events Effects

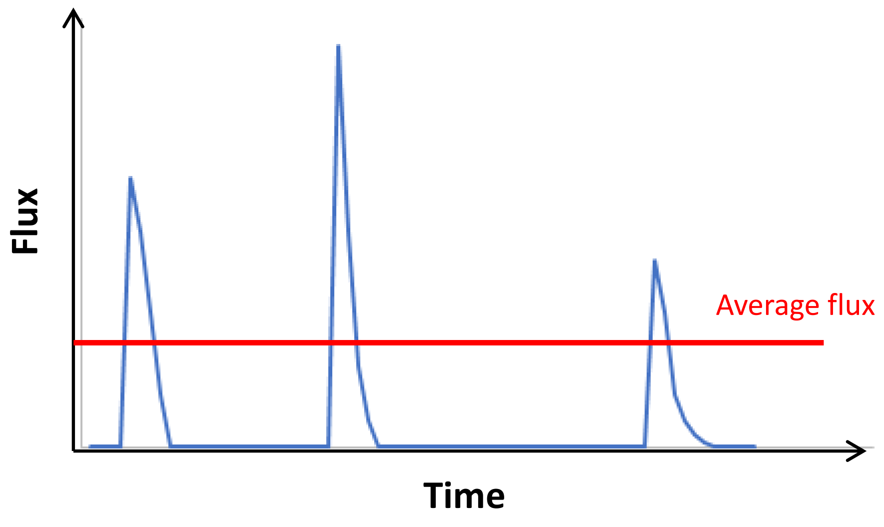
- Each family model is built in a different way and depends on different parameters.

Average models

- The spectrum corresponds to :
  - Average value during the mission
  - A fluence (rather than flux)

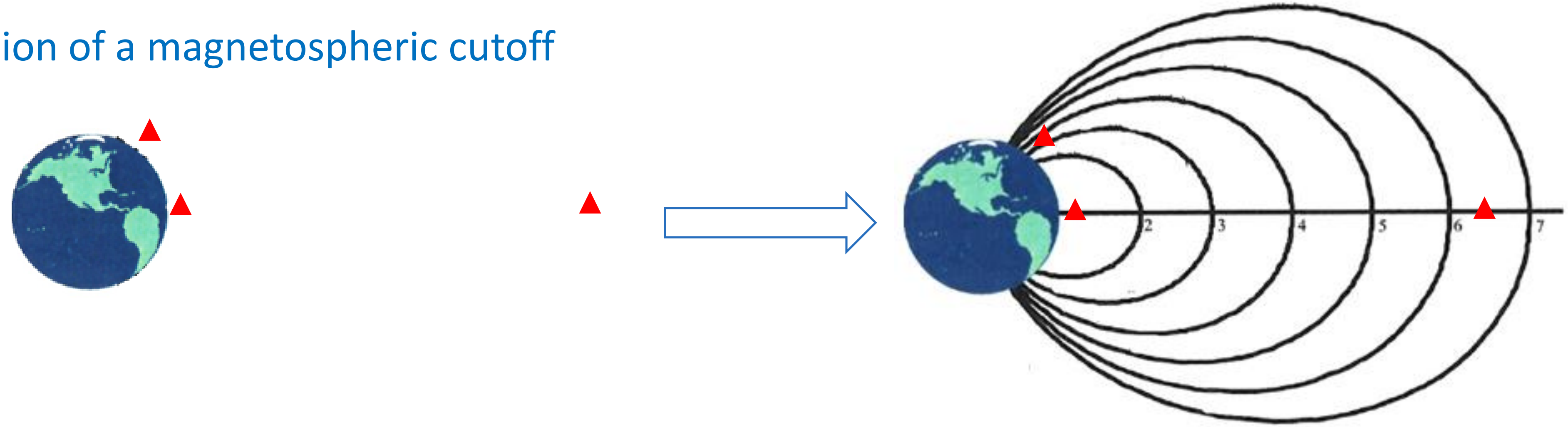
- Features:
  - Used for dose calculation
  - Two parameters:
    - Confidence level
    - Solar active period

- Models give the spectra:
  - At earth level (1AU)
  - No magnetospheric shielding

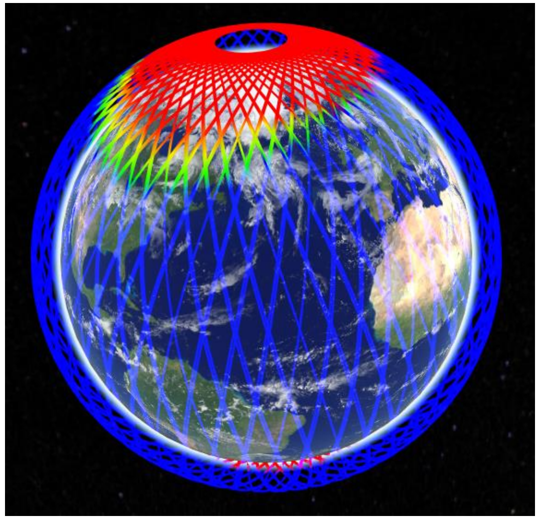


Magnetospheric cutoff

- Application of a magnetospheric cutoff



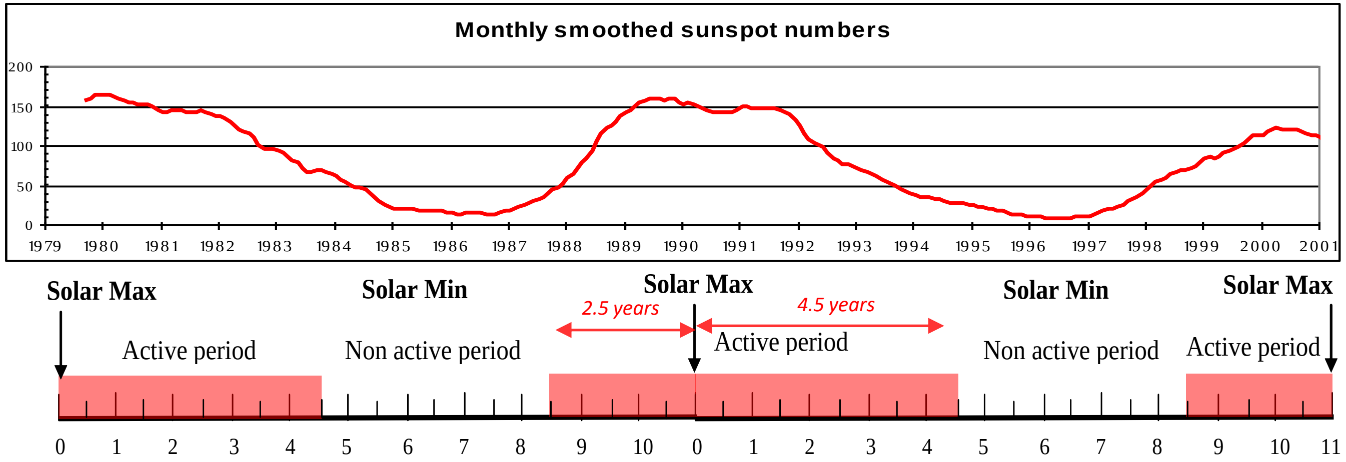
- The model returns the spectra at Earth level
  - Same for all position on the orbit
  - A magnetospheric cut-off must be applied
- When applying the cut-off model
  - Flux depends on the orbit and position on the orbit
  - The mean flux can be estimated



Parameters

- Confidence level (%)
  - The probability that a satellite does not experience a particle flux higher than the calculated flux level
  - Suggested to use higher confidence levels for short missions and lower confidence levels for long missions

- Solar Active Period (Active years) :
  - Solar flares only during a 7 years period around solar max
  - (sol. max - 2.5) + (sol. max + 4.5) = 7 years



Parameters

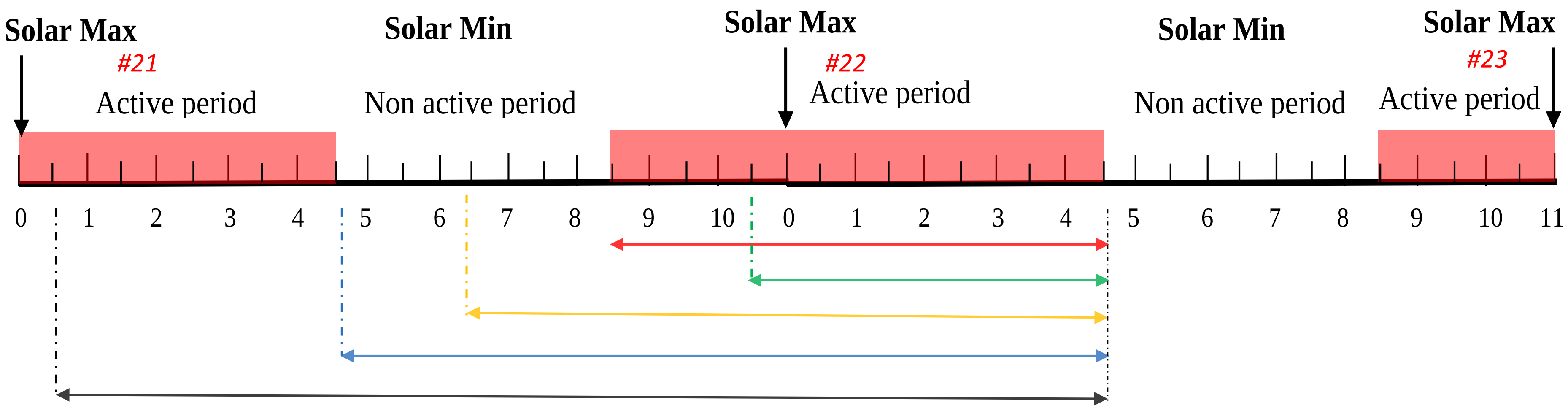
Worst case approach

<u>Number of active years :</u>

One does not know the launch date during the satellite design.

It is suggested to take the worst case :

- 5 years mission, worst case = 5 years (partial active years)
- 9 years mission, worst case = 7 years (complete active years)
- 11 years mission, worst case = 7 years (complete solar cycle)
- 15 years mission, worst case = 11 years (one solar cycle + partial active years)



Average statistical models

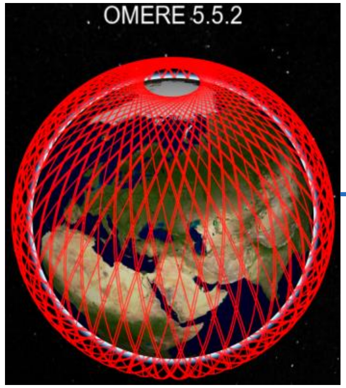
- Average statistical models for solar flare particles

Models	Energy range (MeV)	Data
Protons		
ESP (EU standard)	1 – 300	1966 - 1996
JPL91 (US)	0.5 – 100	1963 - 1991
JPL91 Extended	0.5 - 500	1963 - 1998
SAPPHIRE (ESA)	1-1000	1973 - 2009
SPOF	4 - 110	1974 - 2002
SOLPRO	10 - 100	1964 - 1975
Heavy Ions		
PSYCHIC	10 – 100	1966 - 2001
SAPPHIRE (ESA)	1-1000	1973 - 2009

- Magnetospheric cutoff models

Cutoff models
Störmer
ONERA

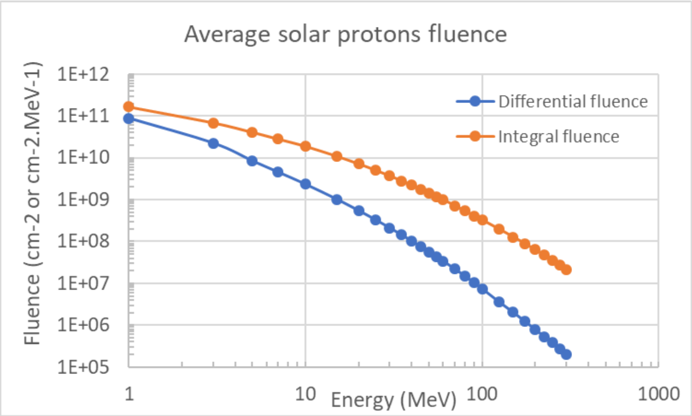
Average statistical models



Inputs

Environment model
[ESP, JPL, SAPPHIRE …]
- Confidence level
- Solar active period

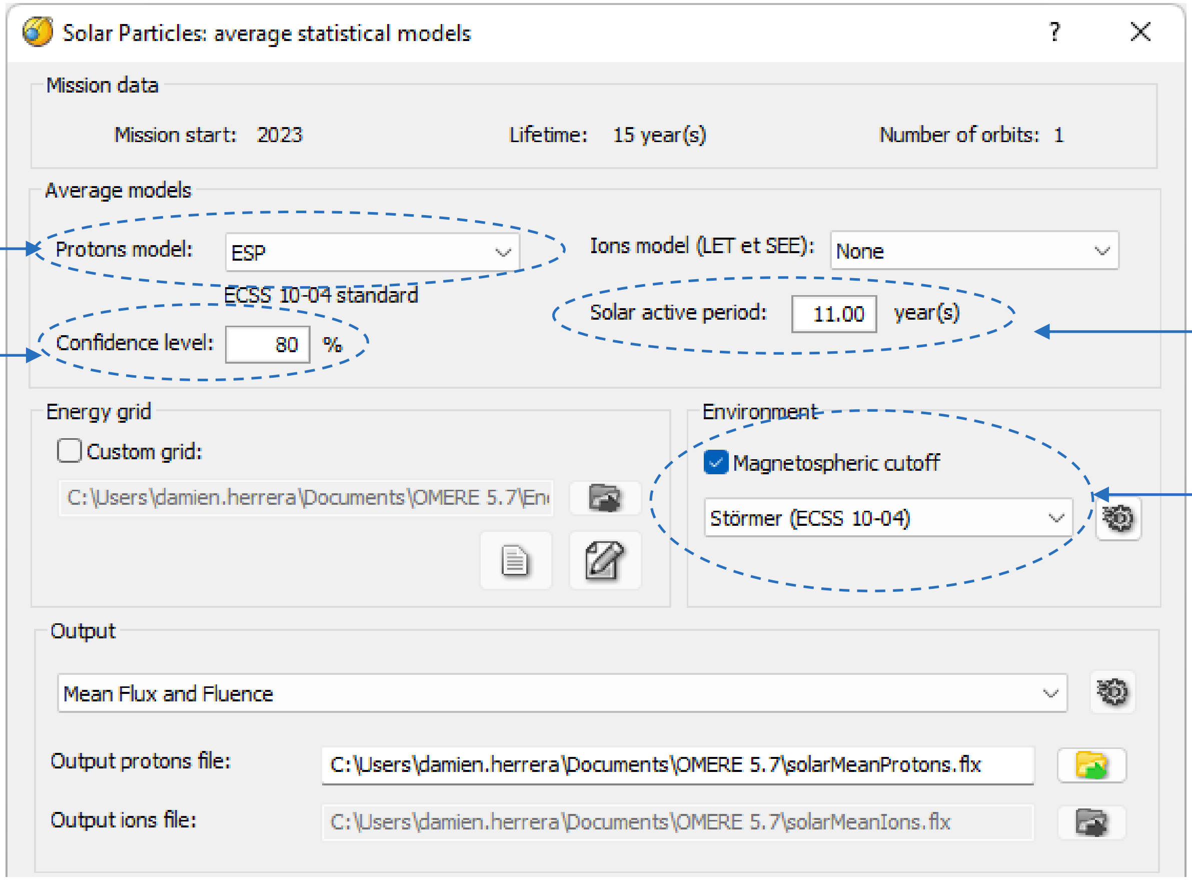
Magnetospheric cutoff model
[Störmer, ONERA]



Energy spectrum

Average statistical models

- Dealing with average statistical models in OMERE



Choose the model

Set the confidence level parameter

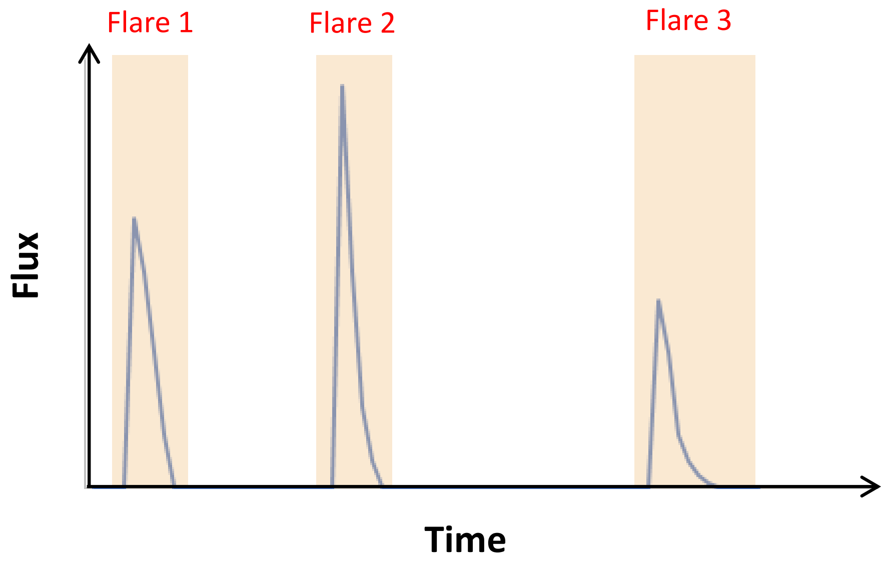
Set the number of solar active years

Select the magnetospheric cutoff model

Flare models

- The spectrum corresponds to:
  - The flux during an actual event

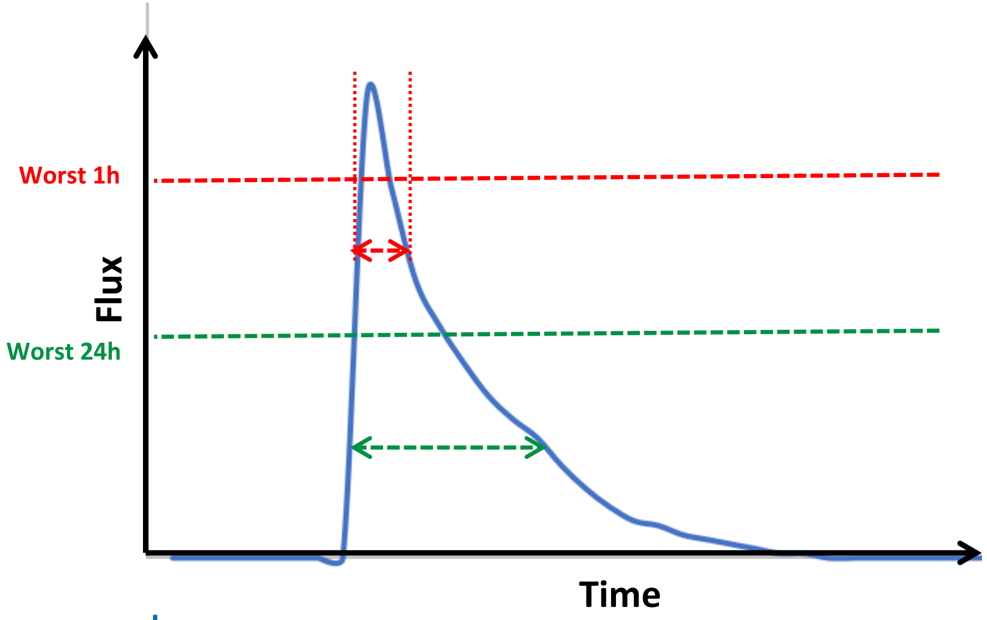
- Features:
  - Used for SEE calculation
  - Different sub-models
    - Worst 5min, 1h, 24h
  - Ions : Z = 1 (H) to Z = 92 (U)



- Models give the spectra:
  - At Earth level
  - No magnetospheric shielding → a cut-off must also be applied.

Flare sub-models

- Each model is composed of different sub-models:
  - Worst 5min
  - Worst 1h
  - Worst day
  - Worst week



- A sub-model with a short duration corresponds to a worst-case
  - Mean flux on a shorter duration
  - Computation made on higher flux level

Flare models

- Classical models

Model	Event(s)	Standard
Protons		
	October 2003	
	October 1989	< 10 ; > 70 MeV
	August 1972	10 – 70 MeV
	July 2000	
ONERA	1974-2002	
SAPPHIRE	1973 - 2009	
Ions (Z = 1 to Z = 92)		
CREME96	October 1989	Yes
CREME86	August 1972	
IOFLAR	September 1977	

For models :

- Worst 5 min
- Worst hour
- Worst day
- Worst week

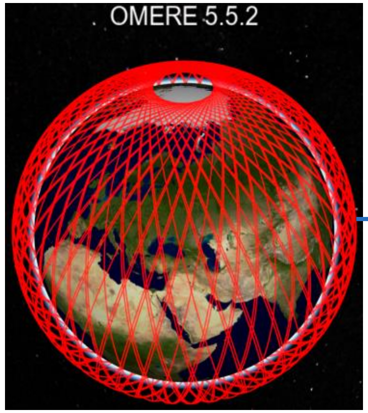
SAPPHIRE – Ions (Z=1 to Z=92):

- Confidence level and active years

- Magnetospheric cutoff models

Cutoff models
Störmer
ONERA

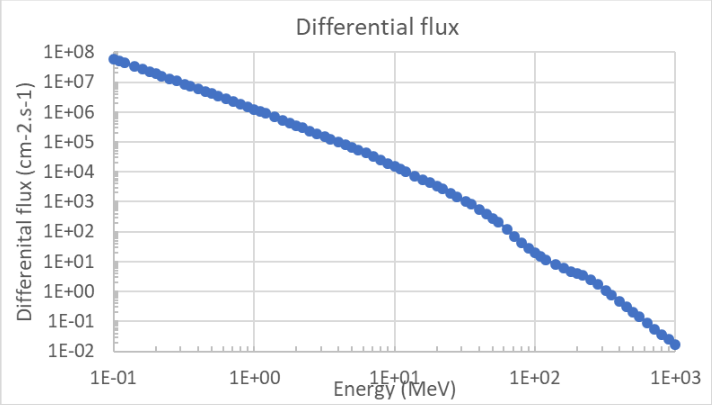
Flare models



Inputs

Magnetospheric cutoff model
[Störmer, ONERA]

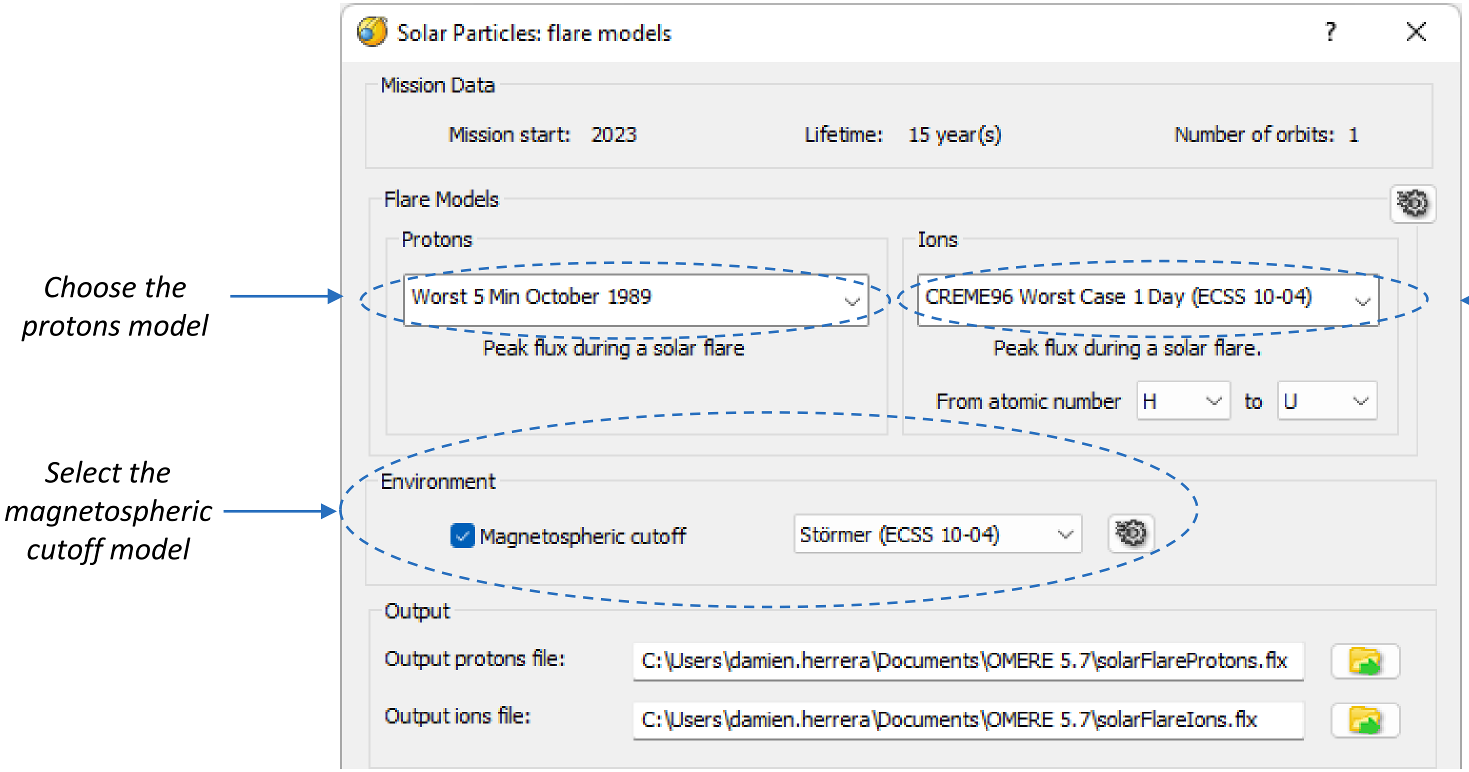
Environment model
[CREME96, SAPPHIRE …]
- Sub-models (5min, day…)
- Elements (for ions only)



Energy spectrum

Flare models

- Dealing with flare models in OMERE



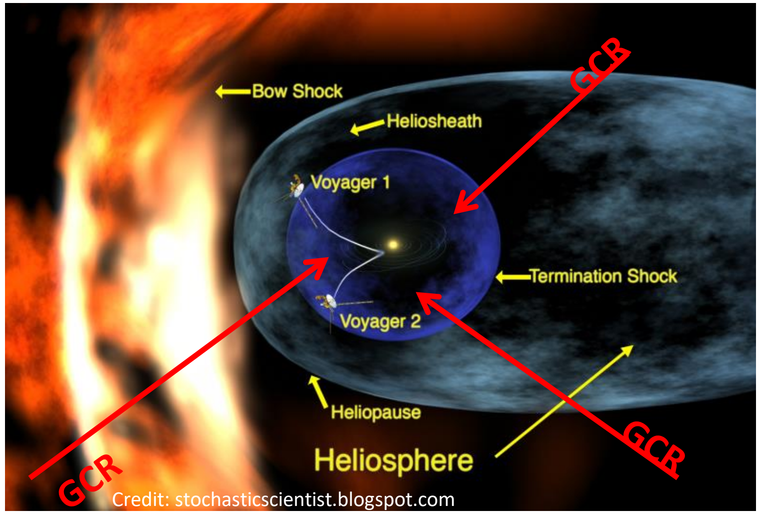
Summary

- Solar particles
  - Protons and ions
  - Up to 300 MeV
- Important for :
  - Interplanetary missions
  - High altitude missions
  - High inclination missions
- Models
  - Statistical models (for dose calculation)
    - Confidence level
    - Solar active period
  - Solar flares models (for SEE rate calculation)
    - worst 5min, 1h, 1day …

Galactic Cosmic Rays (GCR)

Galactic Cosmic Rays

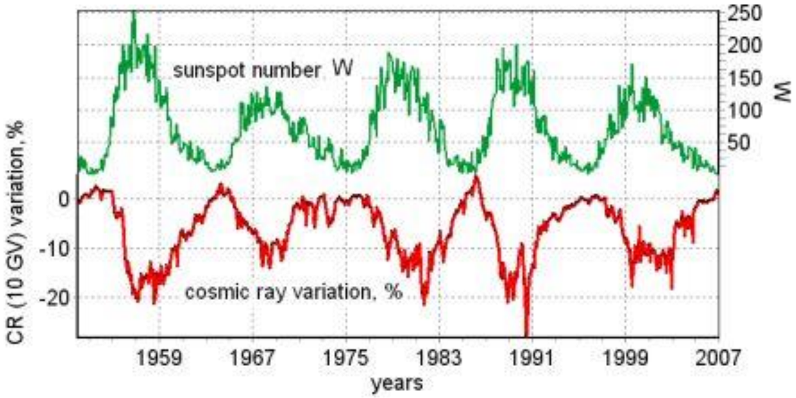
- **Origin** : outside the solar system
- **Acceleration** : interaction with matter shock waves, interstellar magnetic field.
- **Distribution** : homogeneous
- **Energy** : $E \approx 1000$ GeV
- **Composition** : protons (83%), ions (14%), electrons (3%)



- **Flux of cosmic rays anti-correlated with the solar cycle**

- Magnetospheric shielding efficient

  Significant contribution of GCR for :
  - High altitude orbits
  - High inclination orbits
  - Interplanetary trajectories



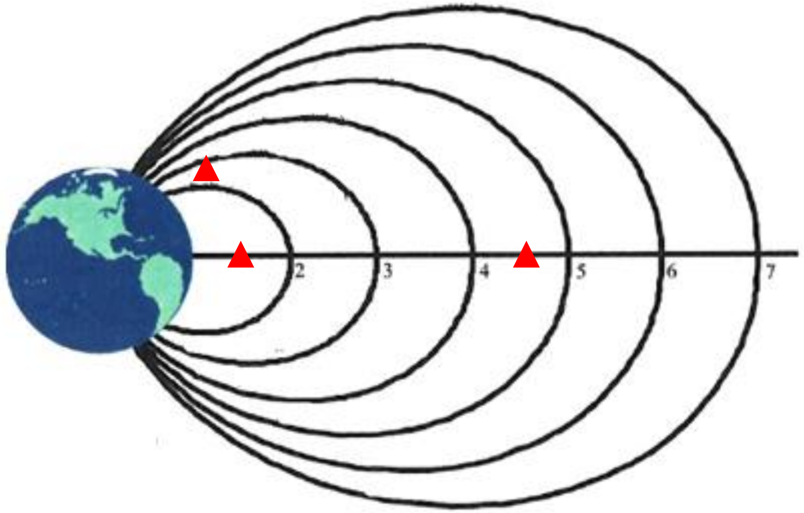
GCR models

- The spectrum corresponds to :
  - Average value during the mission

- Features:
  - Parameters
    - Solar conditions (min = worst case)
    - Ions range (H – U)

- Models give the spectra:
  - At Earth level (wrt the sun)
  - No magnetospheric shielding

- Need for a magnetospheric cutoff



GCR models

- Galactic Cosmic Rays models

Model	Standard
Protons & Ions (Z = 1 to Z = 92)	
CREME96 (US)	Yes
CREME86	-
GCR ISO 15390 (EU standard)	Yes

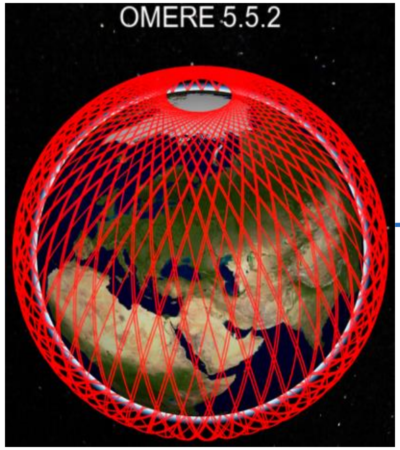
Options:

- Solar Min
- Solar Max
- Mission (weighted)

- Magnetospheric cutoff models

Cutoff models
Störmer
ONERA

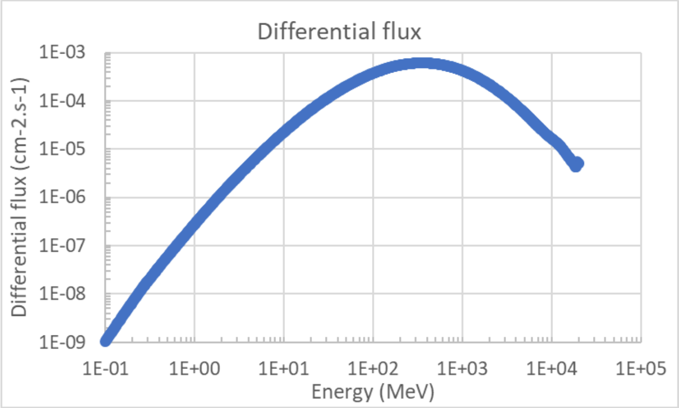
GCR models



Inputs

Environment model
[CREME96, GCR ISO …]
- Solar condition
- Elements

Magnetospheric cutoff model
[Störmer, ONERA]



Energy spectrum

GCR models

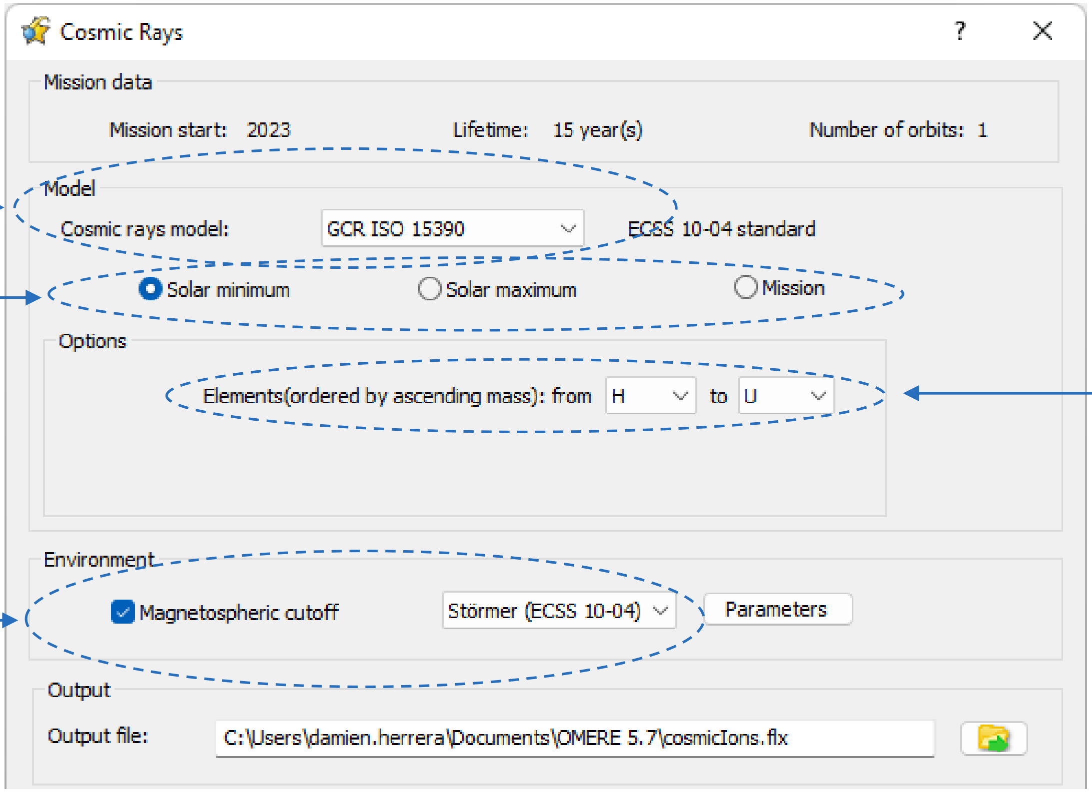
- Dealing with GCR models in OMERE

Choose the model

Select the solar condition

Select the elements to consider

Select the magnetospheric cutoff model

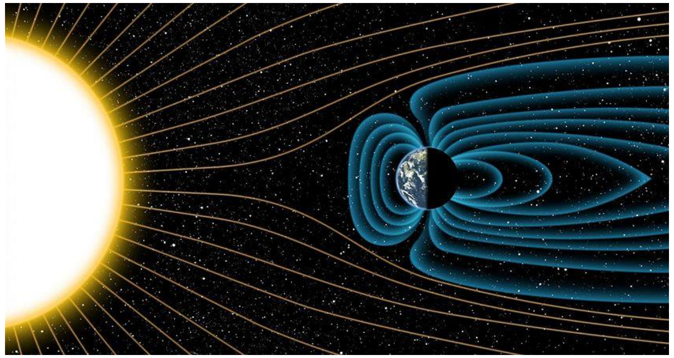


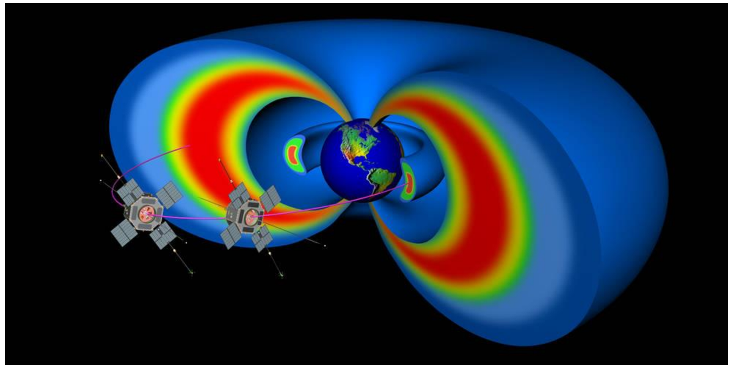
Trapped particles

Introduction

- Magnetosphere acts as a shield
  - It protects us from solar particles and galactic cosmic rays
  - These particles can still impact satellites on:
    - interplanetary orbits
    - orbits with high altitudes
    - orbits with high inclination

- However:
  - Particles (electrons and protons) can be trapped inside the magnetic field
  - They are accelerated to higher energies in the so-called radiation belts

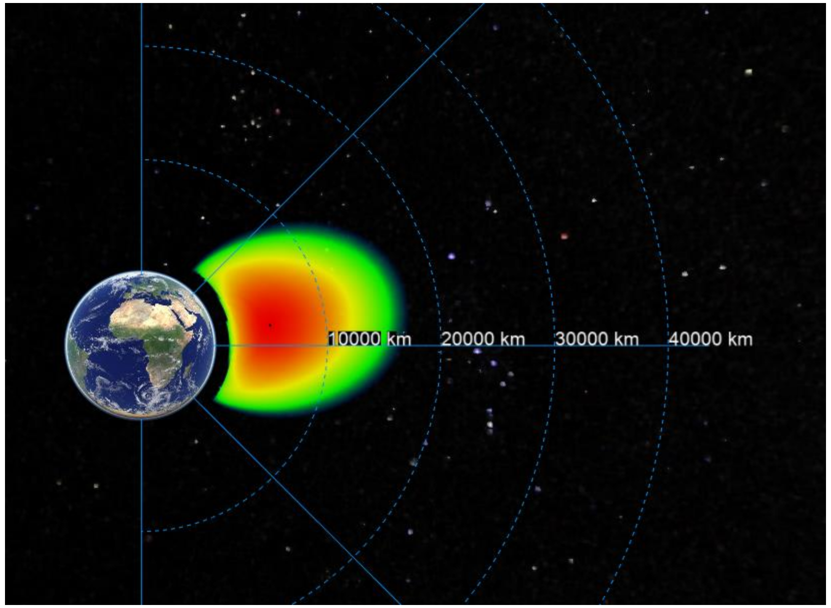




The radiation belts

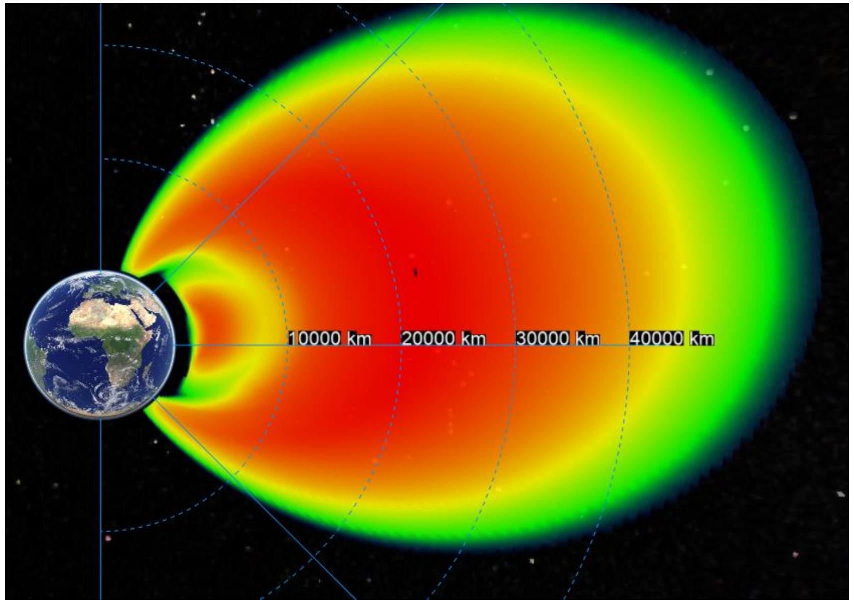
Protons

- **Structure** : one inner belt
- **Energy** : 1 keV – 500 MeV
- **Source** : **GCR** + Solar wind
- **Solar cycle dep.** : anti-correlated



Electrons

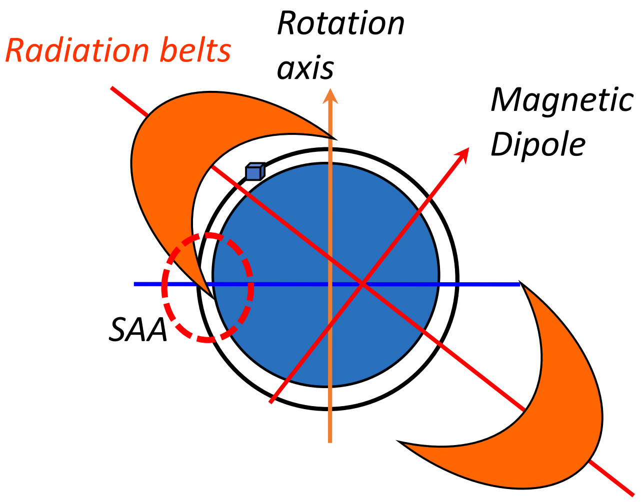
- **Structure** : two belts (inner and outer)
- **Energy** : 1 keV – 7 MeV
- **Source** : **Solar wind**
- **Solar cycle dep.** :
  - LEO : correlated
  - GEO : higher during declining phase



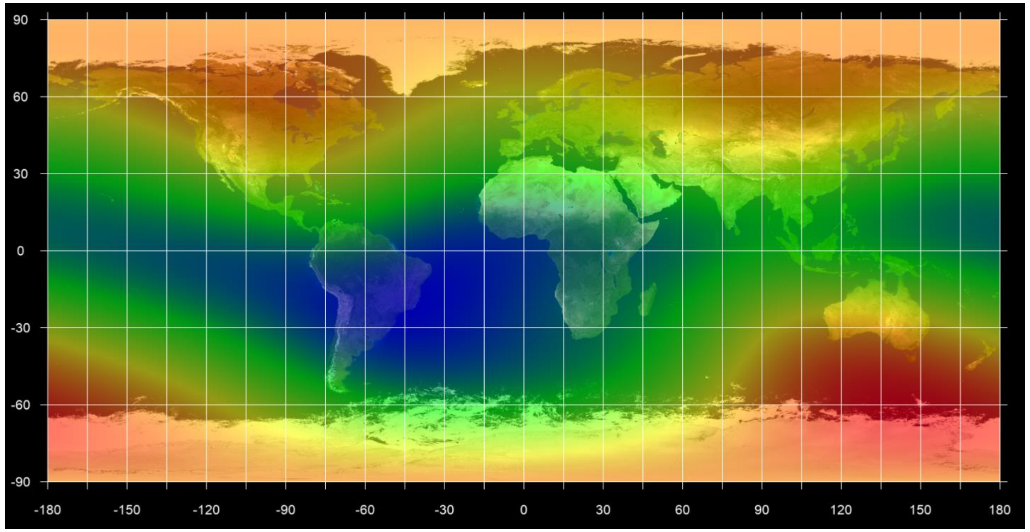
Radiation belts and SAA

- Shift between geographical and magnetic reference frame
  - The radiation belts come closer to the Earth above the south Atlantic ocean

- This corresponds to the region where the magnetic field is the weakest
  - South Atlantic Anomaly



Magnetic field – 800km



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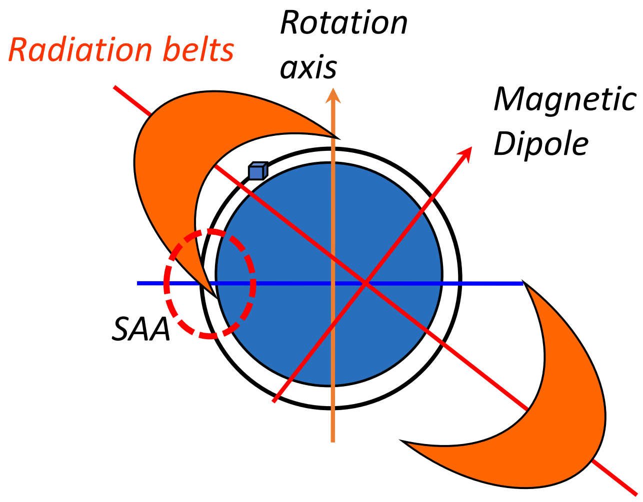
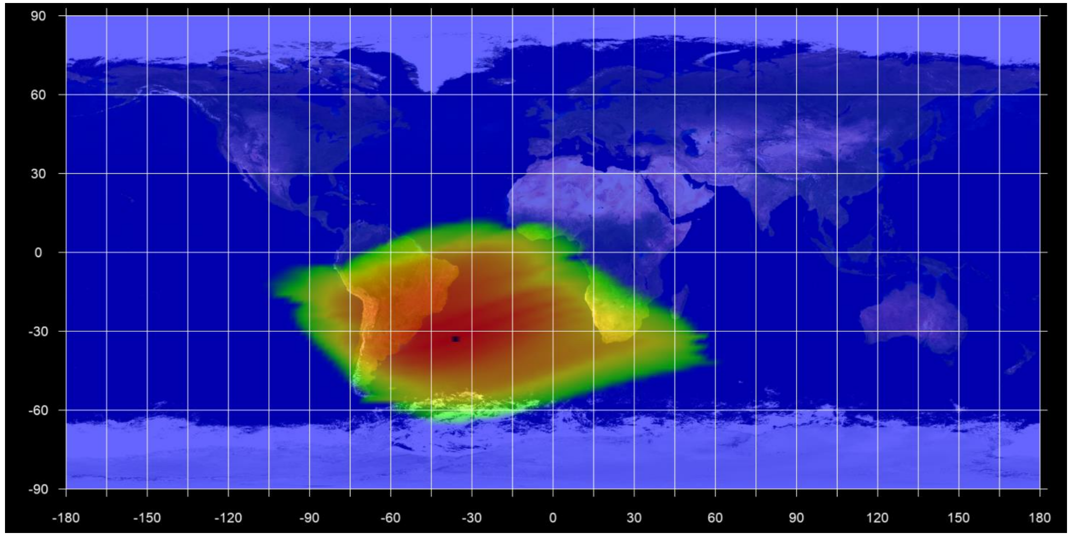


Trapped protons > 10 MeV (AP8) – 800km



- Over the SAA, increase of the flux

Radiation belts and SAA

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  - The radiation belts come closer to the Earth above the south Atlantic ocean

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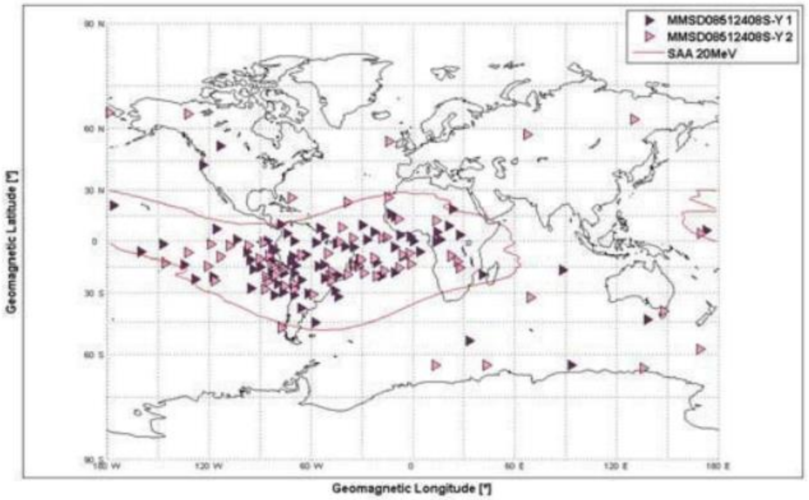
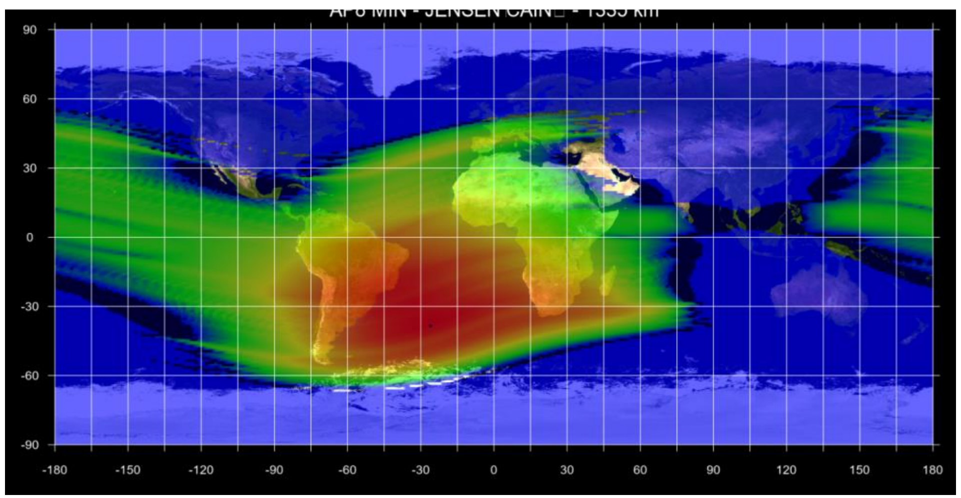
MMSD08512408S-Y SEFI flight data cartography – CARMEN-2



Trapped protons > 10 MeV (AP8 Min) – 1335km



- Over the SAA, increase of the flux → Increase of Single Events

Models: AE8/AP8

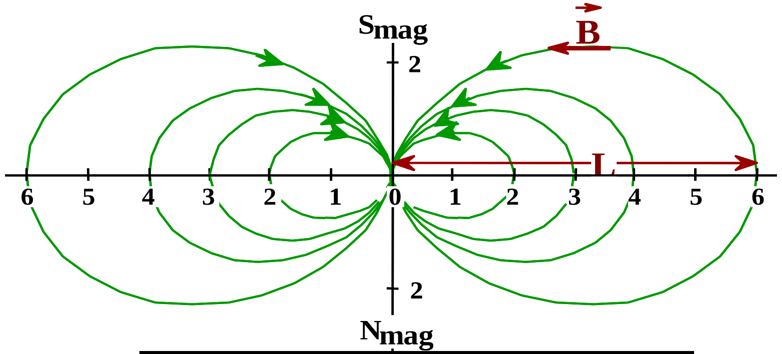
⚠ These models do not depend on the solar cycle variations (no real time variations)

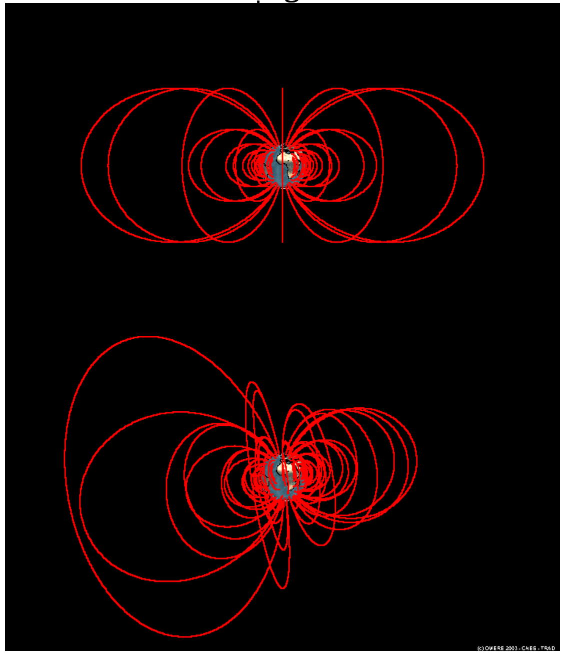
- Two conditions :
  - Solar min
  - Solar max

- Coverage:
  - Space: global $(L = 1 - 8)$
  - Energies:
    - Electrons [0.04 - 7.0] MeV
    - Protons [0.1 - 300] MeV

- OMERE: Maps of integral flux

- ECSS
  - AE8: standard for non-specific orbits (see next slides)
  - AP8: standard for all orbits





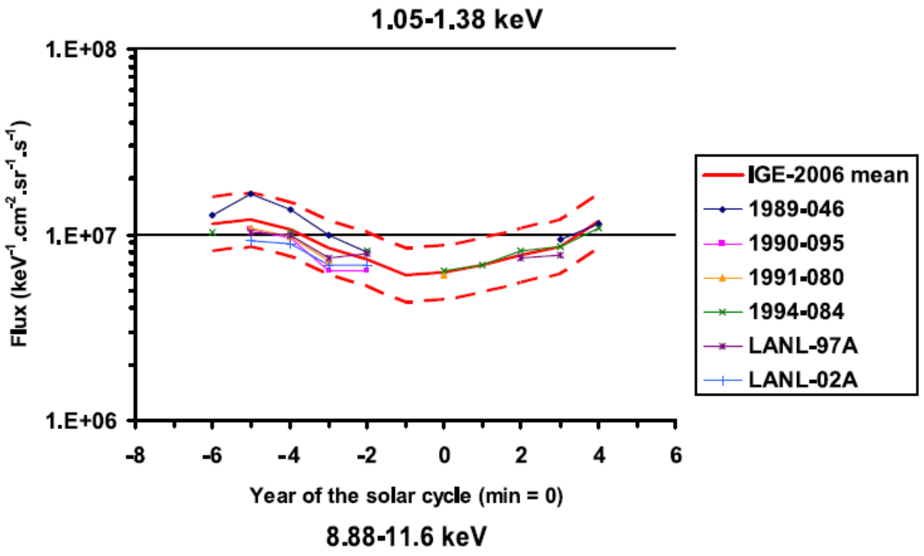
Models: IGE 2006

- Three options:
    - Upper case,
    - Average,
    - Lower case.

- Coverage:
    - Space: GEO orbit $(L = 6.6)$
    - Energies:
        - Electrons [0.001 – 5.2] MeV

- ECSS
    - Standard for GEO orbits ±500km

⚠ Only for GEO orbit, OMERE does not check the positions.



Sicard et al., 2008

Models: MEOv2

- Three options:
  - Upper case,
  - Average,
  - Lower case.

- Coverage:
  - Space: MEO orbit $(L = 4.2)$
  - Energies:
    - Electrons [0.28 – 2.24] MeV

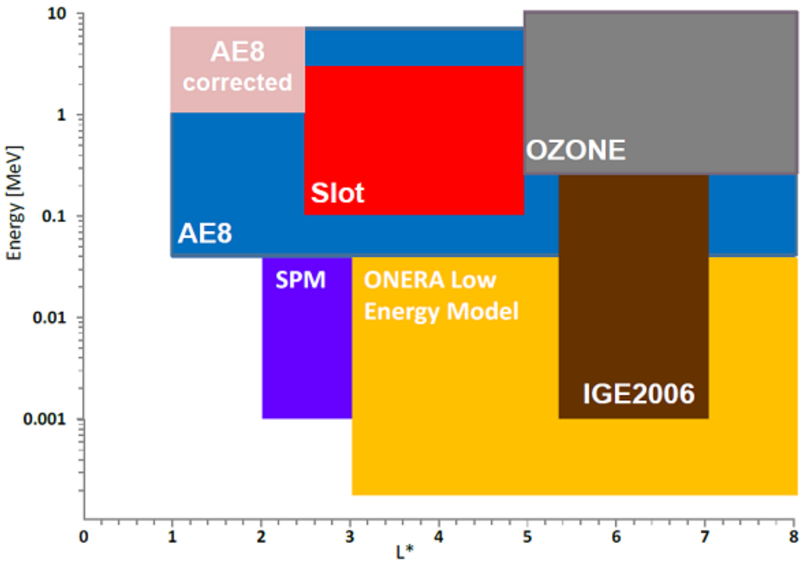
- ECSS
  - Standard for [20 500 km ; 24 000 km] & 55° ± 5°

⚠ Only for MEO orbit, OMERE does not check the positions.

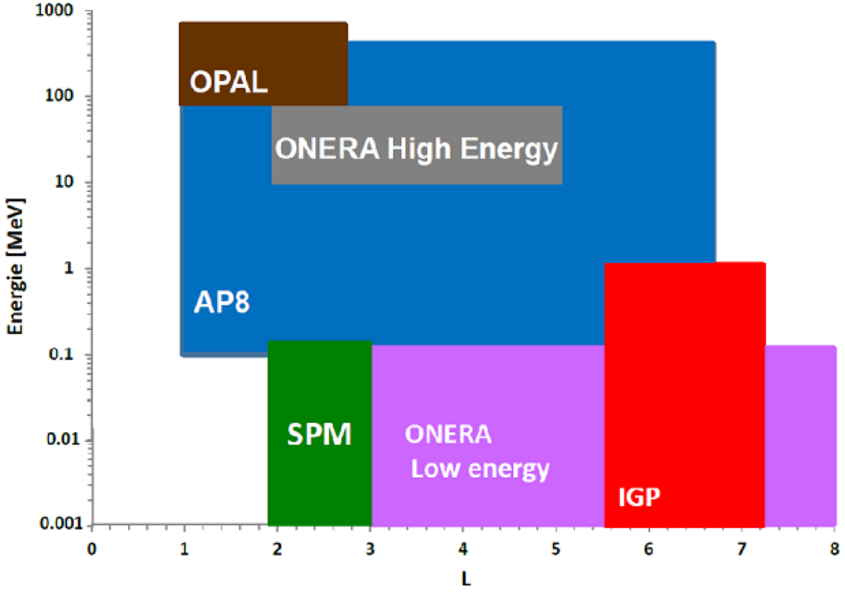
Models: GREEN

- Options/parameters
  - Electrons : Upper case or average
  - Protons : No input

- Characteristics:
  - Global models
  - Patchwork of several others



Electrons



Protons

Summary

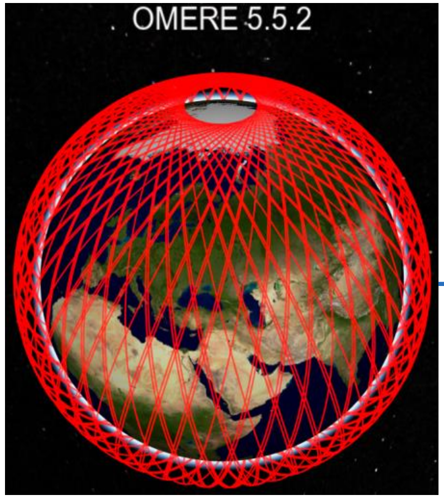
- Global models
  - AE8/AP8
  - AE9/AP9
  - GREEN

- ECSS standards
  - Electrons :
    - GEO orbit: IGE 2006
      - ±500km
    - MEO orbit: MEOv2
      - [20 500 km ; 24 000 km] & 55°±5°
    - Other orbits: AE8 max
  - Protons
    - All orbits: AP8 min

	L	Energies (MeV)
AE8	1 - 8	0.04 - 7
AE9	1 - 8	0.04 - 10
IGE-2006	6.6	0.001 - 5.2
MEOv2	4.2	0.28 - 2.24
OZONE	4 - 8	0.05 - 4
SLOT	2 - 4	0.1 - 3
GREEN-e	1 - 8	0.0002 - 10

	L	Energies (MeV)
AP8	1 - 8	0.1 - 400
AP9	1 - 8	0.1 - 1000
OPAL	< 800 km	80 - 1000
GREEN-p	1 - 8	0.001 -1000

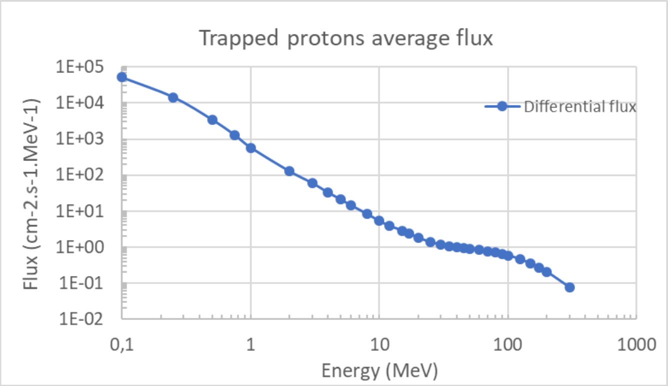
Trapped particles models



Inputs

Environment model
[Ax8, Ax9, GREEN…]
- Parameters (if available)
- For electrons and protons

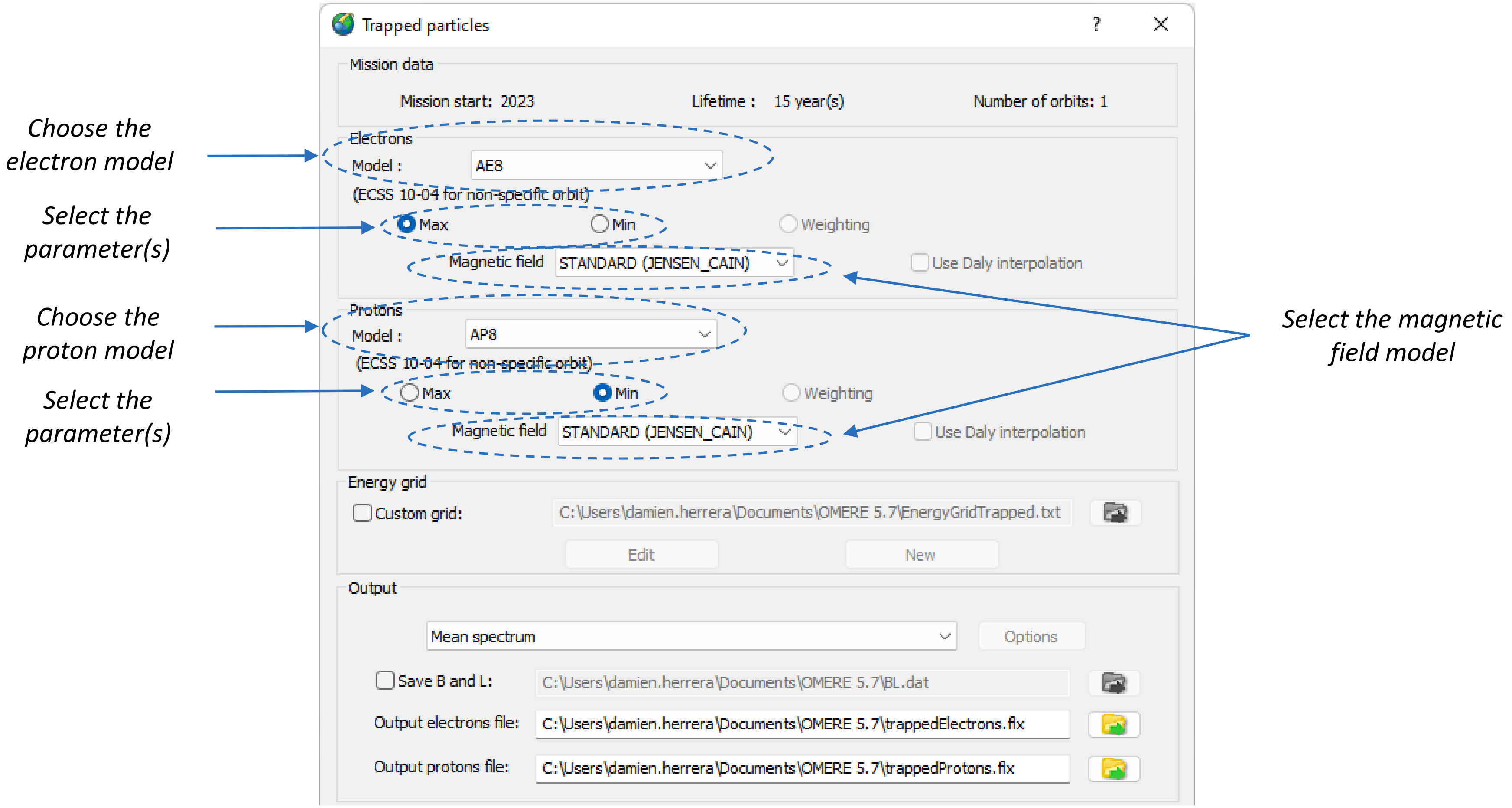
Magnetic field model
[Jensen & Cain 1960, GSFC…]



Energy spectrum

Trapped particles models

- Dealing with trapped particles models in OMERE
  - Magnetic coordinate $(B/B_0, L)$
  - A magnetic field must be selected



Overview of the models

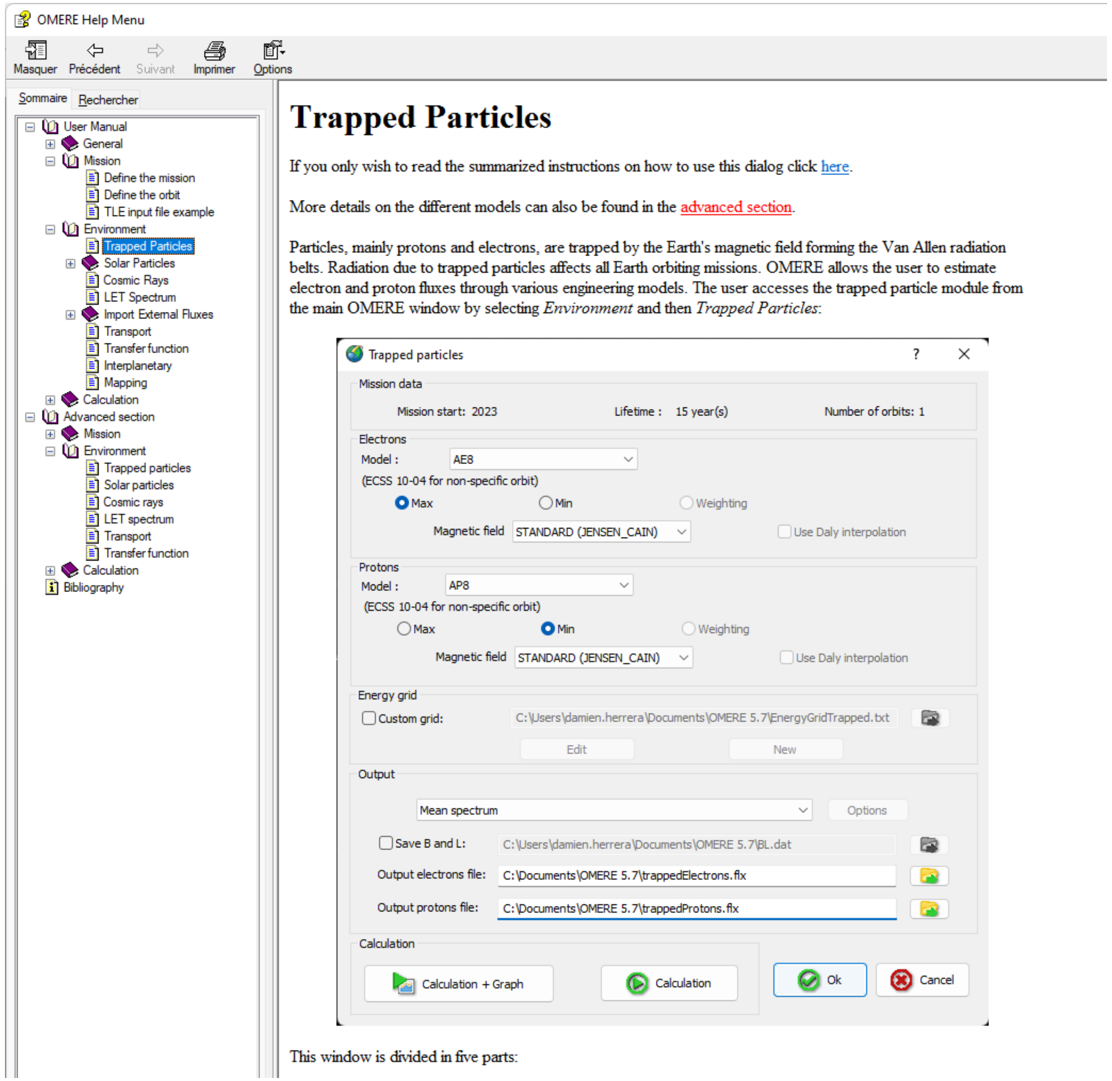
- Models:
  - In-situ measurements
  - Range of validity of L and energy
  - Standards

- Options:
  - Solar min/max
  - Upper/lower case
  - Confidence level [%]
  - Magnetic field
  - Magnetospheric cutoff

- **Cosmic rays**
  - GCR ISO 15390
  - CREME 86
  - CREME 96
- **Solar particles**
  - Protons (average)
    - ESP
    - JPL91
    - JPL91 Extended
    - SOLPRO
    - SPOF
    - SAPPHIRE
  - Ions (average)
    - PSYCHIC
    - Helium
    - SAPPHIRE
  - Solar flare models
- ***Magnetospheric cutoff***
  - Störmer
  - ONERA
- **Trapped particles**
  - Electrons
    - AE8
    - AE9
    - IGE 2006
    - MEO
    - OZONNE
    - SLOT
    - GREEN
  - Protons
    - AP8
    - AP9
    - OPAL
    - GREEN
    - OMEP
- ***Magnetic field***
  - Jensen Cain
  - Dipolar
  - IGRF
  - GSFC

Overview of the models

- Need more information ?



Outside the near-Earth environment

How to manage space environment outside the Earth ?

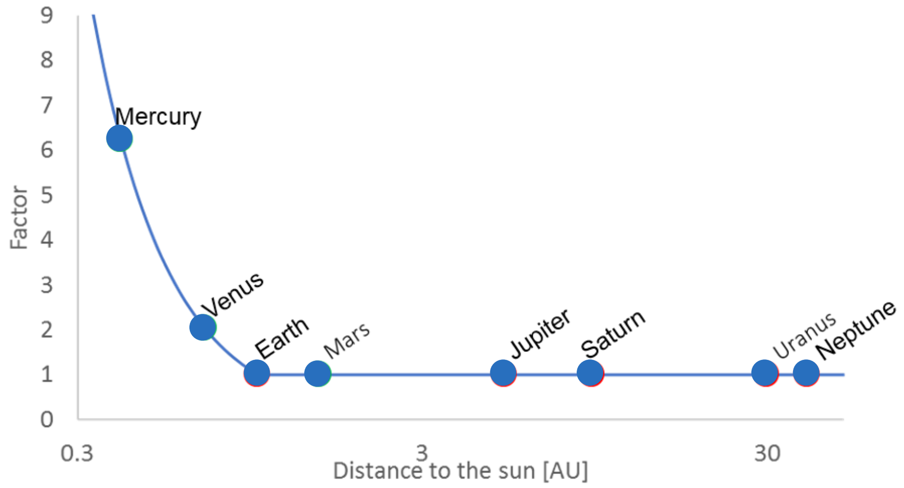
GCR

- The Galactic Cosmis Rays…
  - Constant over the entire solar system
  - Variation wrt the solar cycle are the same for all position

- In OMERE…
  - The models can be used for any other locations in the solar system
  - In practice, disable the magnetospheric cutoff
  - No magnetospheric cutoff for other planets

Solar particles

- Solar particles
  - Flux decreases with the distance to the Sun
  - Attenuation law (ECSS)
    - $1/R^2$ for $R < 1$ AU
    - 1 for $R > 1$ AU : Worst-case beyond the Earth
    - Measurements only at the vicinity of the Earth

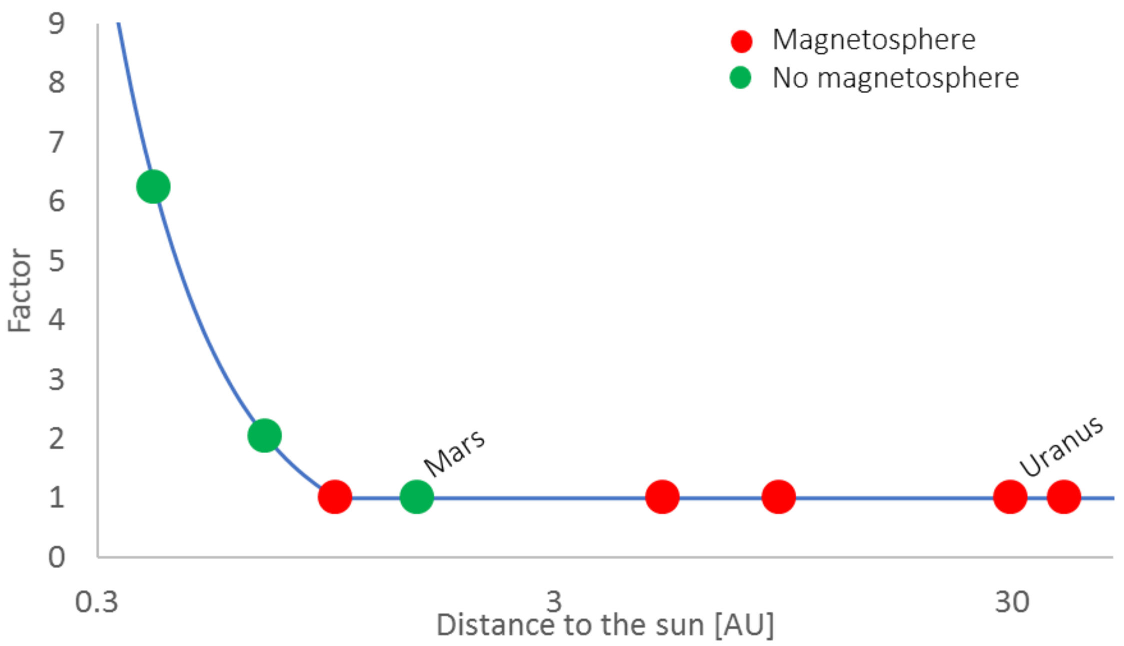


- In OMERE
  - Can be used for any other location in the solar system
  - No magnetic cutoff for other planets

Trapped particles

- Trapped particles
  - Exist for every planet / body with a magnetic field
  - Strongest ones for Jupiter

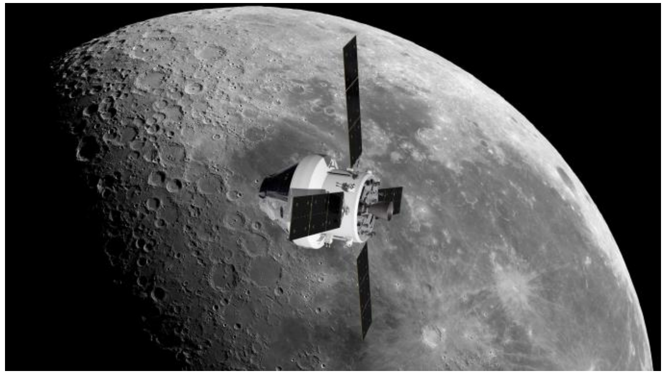
- In OMERE:
  - No trapped particles models for other planets
  - Specific models (not available in OMERE)



Examples

- Moon
  - No magnetic field → no trapped particles
  - Distance to the Earth : 384000km (0.003 AU)

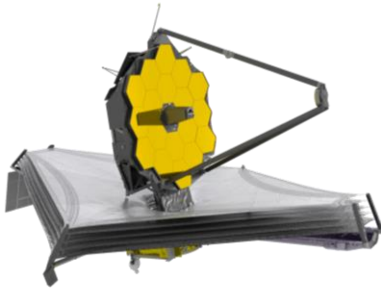
  → Same solar particles than in Earth
  - Same GCR than in Earth (no cutoff)



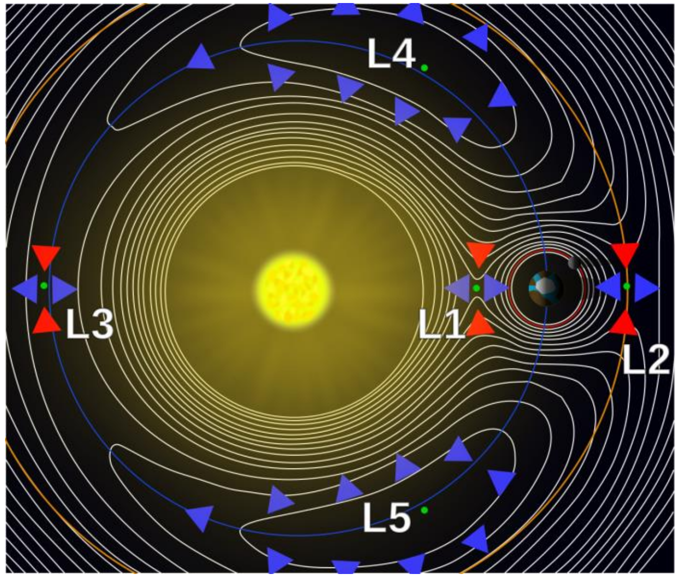
Credits : esa.int

- Lagrangian points
  - No magnetic field → no trapped particles
  - Distance ≈ 1 AU

  → Same solar particles than in Earth
  - Same GCR than in Earth (no cutoff)



Credits : esa.int



<u>Distances:</u>
- Sun – Earth: 150 000 000 km (1AU)
- Earth – L1: 1 500 000 km (0.01AU)
- Earth – Moon: 384 000 km (0.003AU)

Thank you for your attention

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